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SELF-QUENCHING STREAMER MODE IN QUENCHING GASES INITIATED BY ALPHA PARTICLES

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Давыдов Ю. И., Опеншоу Р. E13-2009-28
Самогасящийся стримерный режим в гасящих газах,
инициированный альфа-частицами

Переход из пропорционального в самогасящийся стримерный режим в зависимости от длины и угла наклона трека исследовался в однопроволочной камере, наполненной диметилэфиром или изобутаном. Камера облучалась альфа-частицами от ^{241}Am. Многостримерные события в диметилэфире от альфа-частиц, входящих в камеру под углом 20° с длиной треков 4 мм, дали оценку величины мертвой зоны, определяемой как произведение нечувствительной длины проволоки и мертвого времени, меньше чем 0,1 мкс $\cdot$ см. Эта величина на 3 порядка меньше значений мертвых зон, полученных другими группами для смесей на основе инертных газов. В чистом изобутане двойные стримеры не наблюдались.

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Self-Quenching Streamer Mode in Quenching Gases
Initiated by Alpha Particles

The transition from a proportional to a self-quenching streamer mode, as a function of track length and angle, was investigated in a single-wire chamber filled with either pure DME or isobutane. The chamber was irradiated with ^{241}Am alpha particles. An investigation of multistreamer events in DME due to alpha particles entering the chamber at 20° with track length 4 mm gave an estimate of a dead zone, defined as the product of dead length and dead time, to be less than 0.1 μs $\cdot$ cm. This value is 3 orders of magnitude less than those observed by other groups for noble gases based mixtures. No second streamers were observed with pure isobutane for similar tracks.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR, and at TRIUMF, Vancouver, Canada.

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INTRODUCTION

The TWIST experiment [1] at TRIUMF utilizes drift chambers filled with pure dimethylether (DME) [2, 3] and a low pressure time expansion chamber system filled with pure iso-C_4H_{10} [4]. The need to understand the behaviour of the chambers motivated a study of the gas parameters and wire-chamber operation at different environmental conditions and high voltages up to high current mode. In particular, it led to a systematic study of a self-quenching streamer (sqs), or limited streamer mode in these quenching gases.

The investigation of a sqs mode has a decades long history. This kind of discharge was observed for the first time in the 1970s [5, 6] and has been extensively studied by different groups [7–10]. A few models were proposed to explain the sqs discharge (see, for example, [7,9,11–13]). However, the discharge is not yet fully understood. So it is still important to continue the study of this type of discharge.

Quenching gases effectively absorb photons emitted from the excited atoms in the gas mixtures and thus limit the development of sqs discharges. In pure quenching gases, no transitions from proportional to sqs mode, due to X-ray and beta particle ionization, have been observed. However, observations of sqs signals in some pure quenching gases due to alpha particles have been reported in a number of papers (see, for example, [14–16]). Quenching gases do not emit photons able to ionize their own atoms. However, the first papers reporting transition to sqs mode due to alpha particle ionization tried to explain the transition from proportional to sqs mode by emitted high energy photons [14]. More recently, a model taking into account only ionization electrons from the alpha particle tracks has been proposed [15, 16].

Earlier we reported results of a study of the transition from a proportional to sqs mode in single-wire chambers with different wire diameters and filled with pure quenching gases of DME or iso-C_4H_{10} [17]. DME and isobutane are well known as excellent quenchers. Chambers were irradiated with alpha particles from a ^{148}Gd source with the energy of 3.18 MeV. We demonstrated that chambers filled with DME and iso-C_4H_{10} gases operate in sqs mode with no visible photon contribution at least at studied applied voltages. Our conclusion agrees with a model proposed in [15, 16]. Observation of double streamer signals in DME filled chambers due to inclined tracks from alpha particles has motivated further study of these signals. Alpha particles with higher energy allow the study of multistreamer events as a function of track length and angle. This paper continues the study with alpha particles from the ^{241}Am source.

1. EXPERIMENTAL RESULTS AND DISCUSSION

1.1. Experimental Setup and Procedures. A single-wire chamber with square 12×12 mm cross section and 50 μm diameter gold plated tungsten wire was employed to carry out the tests. The chamber was made of aluminum alloy with 6.35 μm thick aluminized mylar windows on two sides. The wire length was approximately 20 cm. Positive high voltage was applied to the wire.

Instrument grade (0.995 purity) DME and isobutane gases were used in the tests. All tests were made at atmospheric pressure.

An ^{241}Am alpha source was used for all tests. The collimated alpha source was placed directly over the wire in such a way that the wire and alpha particle tracks are near co-planar. Alpha particles entered the chamber either normally or at 20° as schematically presented in Fig. 1. Track lengths inside of the chamber cell were selected by moving an ^{241}Am source away from and towards the chamber. The ion range-energy code SRIM [18] was used to estimate the alpha particle track ranges and energy losses inside of the chamber cell.

All tests were done in a self-triggered mode. Current preamplifiers with different gains (A1 and A2, see Fig. 1) were used for the proportional and sqs modes and in the transition region. Amplified signals were split and one part was sent to the ADC input through the delay line (delay) and attenuator (attn). The second part of the split signal was sent to the extra amplifier A3 (used at low voltages at proportional mode only) and discriminator D. Gate generator (GG) provided the «Start» signal for the data acquisition system and an ADC gate. A LeCroy 2249W model ADC was employed for the tests. The ADC gate signals had a duration of 2.5 μs.

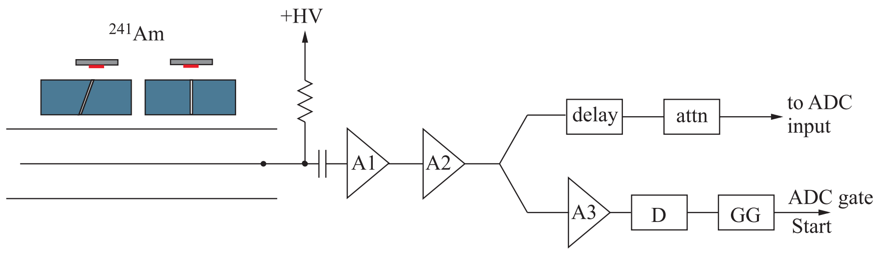

Fig. 1. The block diagram of the test setup

Charge spectra were taken for different applied voltages. Single peaks related to a proportional mode were observed in both gases at low applied voltages. Increasing the high voltage resulted in a transition from proportional to sqs mode in both DME and iso-C_4H_{10} gases. Both proportional and sqs signals co-exist in the transition region. Charge spectra in the transition region have two peaks due to proportional and sqs signals. The fraction of events in the sqs peak increases, while proportional signals moved up to the sqs peak with high voltage increase as demonstrated in Fig. 2 for DME gas at 2200, 2250, 2300 and 2350 V applied voltages. The chamber was irradiated with normally incident alpha particles with 4 mm track lengths inside the chamber cell.

For all measurements, mean charge values in the proportional and sqs peaks were found by fitting the corresponding charge spectra.

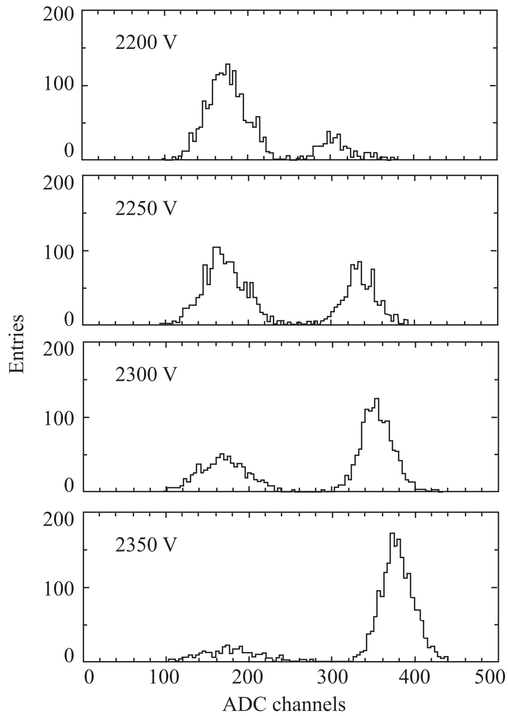

Fig. 2. Measured charge spectra in the transition region for different applied voltages in pure DME filled chamber with 50 μm diameter anode wire. Chamber is irradiated with normally incident alpha particles from ^{241}Am with 4 mm track lengths inside the chamber. Events from the proportional peak (left) move up to the sqs peak (right) upon high voltage increase

1.2. Results and Discussion. Figure 3 shows the collected charge as a function of high voltage in pure iso-C_4H_{10} filled chamber. Alpha particles entered the chamber normally. Track lengths inside the chamber volume were 1, 3, 4 and 5 mm. The transition from proportional to sqs mode starts earlier on the longer tracks, where initial and total charges are bigger. It is interesting to notice that the difference in the sqs mode between 1 and 3 mm long tracks is much bigger than that between 3 and 4 and 5 mm. In the case of a short track, it seems that the sqs signals are not developed totally. Small differences between the sqs signals from 3, 4 and 5 mm tracks could indicate that only part of ionization electrons from the long tracks are contributing to the formation of the sqs signals.

Differences in the collected charges in pure iso-C_4H_{10} due to 4 mm long tracks from alpha particles entering the chamber volume normally and at 20° are

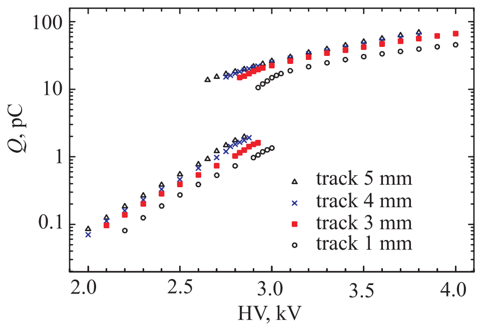

Fig. 3. Measured charge as a function of high voltage in pure iso-C_4H_{10} filled chamber with 50 μm diameter anode wire. Chamber is irradiated with normally incident alpha particles from ^{241}Am. Track lengths inside the chamber are 1, 3, 4 and 5 mm

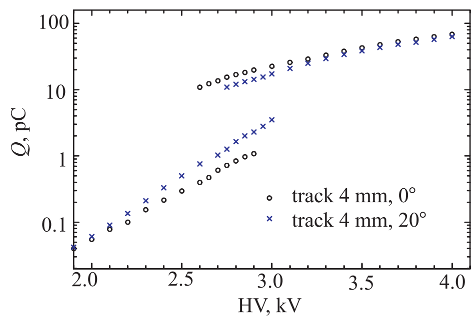

Fig. 4. Measured charge as a function of high voltage in pure iso-C_4H_{10} filled chamber. Chamber is irradiated with alpha particles from ^{241}Am entering at 20°. Track lengths inside the chamber are 4 mm

shown in Fig. 4. Projection of such a 4 mm inclined track on the wire length is about 1.37 mm. Initial ionizations are similar for both cases. However, the space charge influence in the proportional mode is higher for normal tracks, resulting in smaller collected charge compared with that for inclined tracks. Transition to the sqs mode happens at lower voltage for normal tracks, and their collected charge at the beginning of the sqs mode is bigger. Further high voltage increase resulted in the equalization of collected charges from both types of tracks. Again, this could indicate that only part of the ionization electrons from the track are contributing to the sqs signal.

DME gas is an even better quencher than pure iso-C_4H_{10}. Collected charge as a function of high voltage for pure DME is depicted in Fig. 5. The chamber was irradiated with normally incident alpha particles, track lengths are 1, 3, 4 and 5 mm. As in case of pure iso-C_4H_{10}, the transition from proportional to sqs mode starts earlier on the longer tracks. In the sqs mode, the

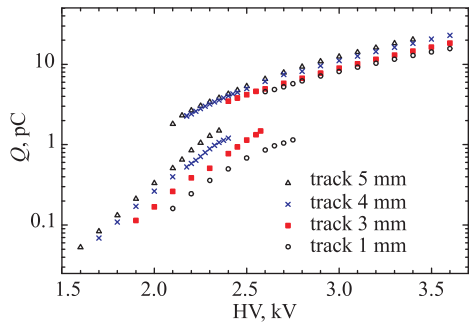

Fig. 5. Measured charge as a function of high voltage in pure DME filled chamber. Chamber is irradiated with normally incident alpha particles from ^{241}Am. Track lengths inside the chamber are 1, 3, 4 and 5 mm

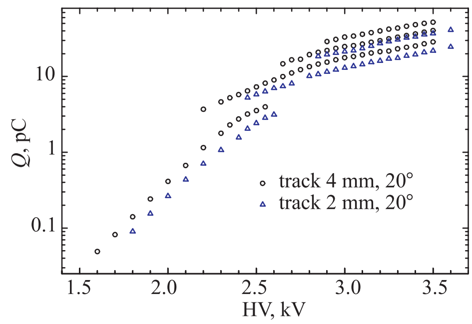

Fig. 6. Measured charge as a function of high voltage in pure DME filled chamber. Chamber is irradiated with alpha particles from ^{241}Am entering at 20°. Track lengths inside the chamber are 2 and 4 mm

jump between 1 and 3 mm or 4 and 5 mm is smaller than that between 3 and 4 mm. This could indicate that sqs signals from 1 and 3 mm long tracks are not fully developed.

In DME, for alpha particles entering the chamber volume at 20° the situation differs from that for isobutane. Similar to iso-C_4H_{10}, in DME for both 2 and 4 mm long alpha particle tracks high voltage increase resulted in the appearance of sqs signals. Further high voltage increase resulted in the appearance of double sqs signals for both track lengths. In the case of double sqs signals, two streamers are separated by a few hundred nanoseconds. Even triple sqs signals appeared due to 4 mm long tracks. As has been demonstrated in [17], these double and triple

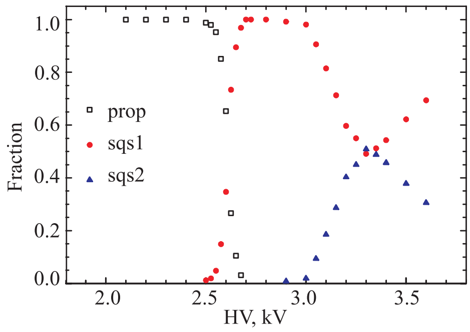

Fig. 7. Fractions of proportional (prop) as well as single (sqs1) and double (sqs2) sqs signals as a function of high voltage in a pure DME filled chamber. Chamber is irradiated with alpha particles from ^{241}Am entering at 20°. Track lengths inside the chamber volume are 2 mm

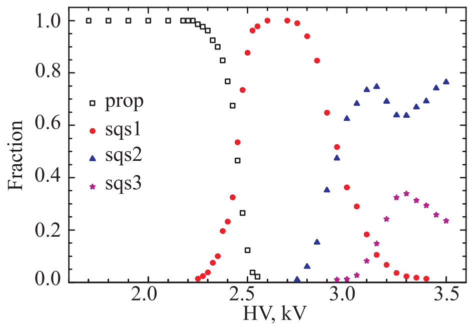

Fig. 8. Fractions of proportional (prop) as well as single (sqs1), double (sqs2) and triple (sqs3) sqs signals as a function of high voltage in a pure DME filled chamber. Chamber is irradiated with alpha particles from ^{241}Am entering at 20°. Track lengths inside the chamber volume are 4 mm

sqs signals are solely due to ionization electrons from the alpha particle tracks. Collected charges from 2 and 4 mm long tracks from alpha particles entering the chamber at 20° are shown as a function of high voltage in Fig. 6.

The fractions of proportional and sqs signals in DME gas as a function of high voltage for 2 and 4 mm long tracks are shown in Fig. 7 and Fig. 8, respectively. In the case of 2 mm tracks, proportional signals (prop) at first transfer to 100% sqs (sqs1). Further high voltage increase resulted in the appearance of double sqs signals (sqs2), while decreasing the fraction of single sqs signals. The fraction of double sqs signals reaches a maximum, and then decreases. Two reasons could be responsible for such a behaviour. First, the high voltage increase causes bigger avalanche size in the first sqs signals, which results in an increase of dead length and dead time. The second possible explanation is the decrease of the electron drift time spread and the involvement of most of the initial ionization electrons in the first sqs avalanche. Thus, an insufficient number of electrons remain to develop the second sqs discharge (notice that in DME, photons do not play any visible role in the formation of the sqs discharge).

Similar transitions occur in the case of 4 mm long tracks (Fig. 8). At first, proportional signals (prop) transfer to 100% single sqs signals (sqs1). Double (sqs2) and then triple (sqs3) sqs signals appear with increasing high voltage. As a result, the fraction of single sqs signals decreases, and eventually goes to 0. The fraction of triple sqs signals increases to some maximum value, and then goes down with further high voltage increase. This behaviour could again be explained by an increase of dead length and dead time due to bigger charge size, as well as by smaller drift time spread of the ionization electrons.

The main reason for differences between DME and iso-C_4H_{10} is the difference in the electron drift velocities in the two gases. The electron drift velocities of both gases are nonsaturated. At operating voltages the reduced electric field

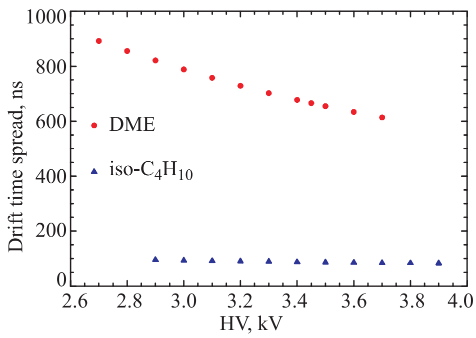

Fig. 9. GARFIELD estimation of drift time spread in DME and iso-C_4H_{10} as a function of applied voltage

changes from approximately 1 to 10 kV/cm within 90% of the drift cell size. Over that field range the drift velocity in DME changes more than 10 times, while the change for iso-C_4H_{10} is less than 2 times.

Different drift velocities result in essentially different electron drift time spreads, i.e., difference in the drift time between the first and the last electrons from the alpha particle track. In isobutane a drift time spread of ionization electrons from an inclined 4 mm long track in the sqs mode is approximately 80–100 ns, while that for the same track in DME changes from approximately 1000 to 600 ns with high voltage increase. GARFIELD [19] estimations of the drift time spreads in sqs mode for 4 mm inclined tracks are shown for both gases in Fig. 9.

Such a difference in drift time spread could explain the absence of multistreamers in pure iso-C_4H_{10} and behaviour of the multistreamer fractions in the case of DME for inclined tracks. In fact, the drift time spread in pure iso-C_4H_{10} is less than 100 ns, which is comparable to a typical sqs signal width. Thus, all electrons from the alpha particle tracks, which are not involved in the streamer, are collected, while part of the wire in the vicinity of the streamer is insensitive to subsequent electrons. In the case of DME, the fraction of triple sqs signals from the 4 mm tracks increases to some maximum value with high voltage increase, but then drops down. Obviously, this is due to a drift time spread decrease with a high voltage increase.

2. ON THE DEAD ZONE IN THE SQS MODE

In wire chambers operating in sqs mode, the part of the wire in the vicinity of the streamer becomes insensitive to subsequent electrons, i.e., the wire has a dead length δ. This part stays insensitive during the dead time period t_d. The dead zone η in the sqs mode was defined in [7] as the product of dead length and dead time: $\eta = \delta \cdot t_d$.

Typical values of the dead zone obtained by different groups for noble gas based mixtures are within 85–400 μs $\cdot$ cm (see, for example, [7, 20, 21]). In the case of multistreamer events a dead zone η can be estimated by taking into account dead zones for single, double, triple, etc. streamers weighted with their fractions. Thus,

$$\eta = \sum_i f_i \cdot \delta_i \cdot t_{di},$$

where f_i, δ_i and t_{di} are the fraction of events, dead length and dead time for the *i*th streamer multiplicity, respectively.

For iso-C_4H_{10} one can calculate only the lower limit of the dead zone. In fact, a 4 mm long track at 20° has a projection on the wire length of about 1.37 mm. The absence of double streamers in isobutane suggests that the dead length for single streamers in this gas is more than that value, i.e., $\delta_1 > 1.37$ mm, and the dead time is more than the drift time spread, i.e., $t_{d1} > 95$ ns. These numbers give a lower limit for the dead zone in sqs mode in iso-C_4H_{10} at the level $\eta > 13 \cdot 10^{-3}$ μs $\cdot$ cm.

For multistreamer events in DME a dead zone estimation can be made under some simplifying assumptions. For simplicity one can assume that single streamers have a dead length equal to the track projection on the wire and a dead time equal to the drift time spread, double streamers are separated by the length of a track projection on the wire, and triple streamers are equidistant on the same projection. Thus, for estimation purposes, dead lengths for single and double streamers δ_1 and δ_2 will be taken as equal to the projection of the track on the wire, i.e., 1.37 mm. For triple streamers a dead length value δ_3 is half of that for the double streamers. Dead times for single and double streamers t_{d1} and t_{d2} are taken equal to the drift time spreads for given applied voltages. Dead time for triple streamers t_{d3} is equal to half of the drift time spread. It should be noted that these simplified assumptions underestimate contributions to the dead zone from single streamers and overestimate contributions from double and triple streamers.

Dead zones calculated under the above-mentioned assumptions with dead time values taken from the drift time spreads in Fig. 9 and fractions of single, double and triple sqs signals from Fig. 8 are plotted in Fig. 10. At voltages corresponding to the left-most points of the plot, the fraction of single streamers is close to 1 and dead zone values here are well underestimated. The size of this underestimation decreases as the fraction of single sqs signals decreases with a high voltage increase. At $U = 3.3$ kV the fraction of single streamers is close to 0 and the dead zone is defined by contributions from double and triple streamers. At this voltage the dead zone has a minimum value equal to $\eta \approx 0.072$ μs $\cdot$ cm

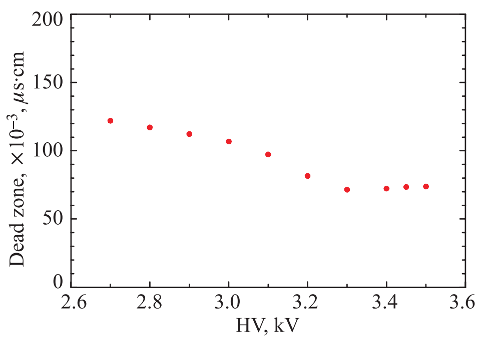

Fig. 10. Estimated dead zone in the tested single-wire chamber filled with DME as a function of applied voltage

and again increases with further high voltage increase. Figure 8 demonstrates that the fraction of triple sqs signals has a maximum at $U = 3.3$ kV. Thus, in the case of DME, both Fig. 8 and Fig. 10 confirm that the dead zone has a minimum value at 3.3 kV and increases with a high voltage increase above 3.3 kV.

The obtained value for the dead zone in pure DME is more than 3 orders of magnitude less than those reported by other groups for noble gas based mixtures [7, 20, 21]. The main reason for such a difference is the large amount of photons emitted in those mixtures. These photons produce many secondary avalanches in the vicinity of the original streamer. Thus, in case of a noble gas based mixture a pure sqs signal is accompanied by the secondary avalanches spread along the wire. These secondary avalanches increase dead length and dead time around the original sqs signal. We believe that dead zone values reported for noble gas based mixtures are mostly defined by these additional avalanches and do not reflect the real dead zone values for the sqs signals themselves.

CONCLUSION

Quenching gases iso-C_4H_{10} and DME both demonstrate 100% transition from proportional to sqs mode due to alpha particle ionization.

Double and triple sqs signals appear in the DME filled chamber due to inclined tracks from alpha particles, as was demonstrated for alpha particles entering the chamber cell at 20°. No second streamers were observed for the same type of tracks in the iso-C_4H_{10} filled chamber. Differences between iso-C_4H_{10} and DME are due to different drift velocities and electron drift time spreads.

The dead zone in the DME filled chamber was estimated from double and triple sqs signals due to inclined tracks. The dead zone depends on the applied high voltage and was found to be about 0.072 μs $\cdot$ cm at the minimum point. This value is more than 3 orders of magnitude less than those obtained by other groups for noble gas based mixtures. These reported dead zone values for noble gas based mixtures are defined by secondary avalanches due to emitted photons and do not reflect real dead zone values for «pure» sqs signals.

REFERENCES

1. TWIST Experiment: http://twist.triumf.ca

2. *Davydov Yu. I. et al.* // Nucl. Instr. Meth. A. 2001. V. 461. P. 68.

3. *Henderson R. L. et al.* // Nucl. Instr. Meth. A. 2005. V. 548. P. 306.

4. *Hu J. et al.* // Nucl. Instr. Meth. A. 2006. V. 566. P. 563.

5. *Charpak G. et al.* // Nucl. Instr. Meth. 1970. V. 80. P. 13.

6. *Brehin S. et al.* // Nucl. Instr. Meth. 1975. V. 123. P. 225.

7. *Alekseev G. D. et al.* // Nucl. Instr. Meth. 1980. V. 177. P. 385.

8. *Battistoni G. et al.* // Nucl. Instr. Meth. 1979. V. 164. P. 57.

9. *Atac M. et al.* // Nucl. Instr. Meth. 1982. V. 200. P. 345.

10. *Iwatani K. et al.* // Nucl. Instr. Meth. A. 1985. V. 241. P. 602.

11. *Zhang L. S.* // Nucl. Instr. Meth. A. 1986. V. 247. P. 343.

12. *Taylor F.* // Nucl. Instr. Meth. A. 1990. V. 289. P. 283.

13. *Zalikhanov B.* // Phys. Part. Nucl. Lett. 2006. V. 3, No. 3. P. 211.

14. *Koori N. et al.* // IEEE Trans. Nucl. Sci. 1986. NS-33. P. 395.

15. *Nohtomi A. et al.* // IEEE Trans. Nucl. Sci. 1994. NS-41. P. 884.

16. *Nohtomi A. et al.* // IEEE Trans. Nucl. Sci. 1995. NS-42. P. 552.

17. *Davydov Yu. I., Openshaw R.* // Nucl. Instr. Meth. A. 2006. V. 557. P. 561.

18. *Ziegler J. F.* SRIM, the Stopping and Range of Ions in Matter Code, Version 2003.26; http://www.srim.org/

19. *Veenhof R.* GARFIELD, a Drift Chamber Simulation Program; http://consult.cern.ch/writeup/garfield

20. *Koori N. et al.* // IEEE Trans. Nucl. Sci. 1990. NS-37. P. 107.

21. *Nochtomi A. et al.* // IEEE Trans. Nucl. Sci. 1992. NS-39. P. 719.

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