Secondary scintillation yield from GEM and THGEM gaseous electron multipliers for direct dark matter search

C.M.B. Monteiro a,*, L.M.P. Fernandes a, J.F.C.A. Veloso a,b, C.A.B. Oliveira b, J.M.F. dos Santos a

a CI, Physics Department, University of Coimbra, 3004-516 Coimbra, Portugal
b IGN, Physics Department, University of Aveiro, 3810-193 Aveiro, Portugal

A R T I C L E I N F O

Article history:
Received 17 October 2011
Received in revised form 2 June 2012
Accepted 25 June 2012
Available online 28 June 2012
Editor: W. Haxton

Keywords:
Xenon scintillation
Argon scintillation
Dark matter
GEM
THGEM
Avalanche photodiodes

A B S T R A C T

The search for alternatives to PMTs as photosensors in optical TPCs for rare event detection has significantly increased in the last few years. In particular, in view of the next generation large volume detectors, the use of photosensors with lower natural radioactivity, such as large area APDs or GM-APDs, with the additional possibility of sparse surface coverage, triggered the intense study of secondary scintillation production in micropattern electron multipliers, such as GEMs and THGEMs, as alternatives to the commonly used uniform electric field region between two parallel meshes. The much higher scintillation output obtained from the electron avalanches in such microstructures presents an advantage in those situations. The accurate knowledge of the amount of such scintillation is important for correct detector simulation and optimization. It will also serve as a benchmark for software tools developed and/or under development for the calculation of the amount of such scintillation.

The secondary scintillation yield, or electroluminescence yield, in the electron avalanches of GEMs and THGEMs operating in gaseous xenon and argon has been determined for different gas pressures. At 1 bar, THGEMs deliver electroluminescence yields that are more than one order of magnitude higher when compared to those achieved in GEMs and two orders of magnitude when compared to those achieved in a uniform field gap. The THGEM electroluminescence yield presents a faster decrease with pressure when comparing to the GEM electroluminescence yield, reaching similar values to what is achieved in GEMs for xenon pressures of 2.5 bar, but still one order of magnitude higher than that produced in a uniform field gap. Another exception is the GEM operating in argon, which presents an electroluminescence yield similar to that produced in a uniform electric field gap, while the THGEM achieves yields that are more than one order of magnitude higher.

© 2012 Elsevier B.V. Open access under CC BY license.

1. Introduction

Rare event detection, as direct dark matter search and neutrinoless double beta decay are high points in contemporary particle physics and cosmology. Giving the low rate and high background nature of these experiments, it is crucial to have the highest possible signal gain in the detector. This reason strongly motivated the development of optical Time Projection Chambers (TPC) relying on electroluminescence (EL), i.e. secondary scintillation produced by electron impact, rather than on secondary charge avalanche as the amplification process for the primary ionisation. In the last decade, we have witnessed the increasing development and application of optical TPCs to direct dark matter search, in large experiments such as XENON, ZEPLIN, LUX and WARP [1–4], and to neutrino-
the secondary scintillation output is important if a different type of readout is considered, such as avalanche photodiodes, substituting for PMTs.

Avalanche photodiodes (APDs) are good candidates for the scintillation readout. They are compact and present low power consumption and high quantum efficiency. In particular, the clear advantage of using APDs instead of PMTs relies on their negligible natural radioactivity necessary for a reduced background – radioactivity levels around 10 mBq/PMT for the Hamamatsu R8520 [10], against around 1μBq/APD for the API APDs used in EXO [11], assuming an APD mass of 0.7 g – a requisite for the next generation large-volume rare event experiments. In addition, the prospect of non-full area illumination is also a strong reason for advocating this scintillation increase. Smaller photosensors will allow better position resolution, but need to be higher in number. A compromise may be found between both parameters [12,13]. For that purpose, in recent years there has been intense research on the application of APDs operating in Geiger mode (GM-APDs) for the readout of the scintillation produced in electron avalanches of THGEMs [14] in liquid or in double-phase optical TPCs ([15–19] and references therein).

For correct detector simulation it is essential to know the exact amount of EL produced in the electron avalanches. In [9] we have calculated the absolute EL yield for GEMs [19] and Micro-Hole & Strip Plates (MHSPs) [20] operating in xenon and a simulation toolkit for electroluminescence assessment in noble gases is being developed [21]. This toolkit allows calculating the scintillation produced by drifting electrons in noble gases and will be useful to simulate the scintillation processes in dual-phase and high-pressure noble gas detectors used for rare event detection or in electroluminescence based TPCs for high-energy physics applications. In this work we present results for absolute EL yields in gaseous argon and xenon for electron avalanches produced in GEMs and THGEMs.

2. Experimental setup

A stainless steel chamber was used to accommodate a GEM or a THGEM and a VUV-sensitive large area avalanche photodiode (LAAPD). The chamber was filled with pure xenon or argon at different pressures and sealed off during the measurements. Fig. 1 schematically depicts the chamber incorporating the GEM/THGEM and the LAAPD for the scintillation-readout. This chamber has already been used in [9]. The drift and induction gaps were 8- and 3-mm thick, respectively, in the GEM setup. For the THGEM studies the same setup was used, the THGEM substituting for the GEM but, in this case, the drift and induction gaps were 6- and 2-mm thick, respectively. While for the GEM setup the LAAPD was used to define the induction plane, for the THGEM setup a stainless steel mesh was used as the induction plane, placed 3 mm above the LAAPD enclosure, Fig. 1. The charge collection on an induction plane, instead of on the GEM or THGEM bottom electrode, has the advantage of choosing a specific charge readout, e.g. with 2D capability, at the cost of losing some electrons to the bottom electrode. On the other hand, the electroluminescence can be higher, by few tens of percent, due to the more intense induction field, resulting in higher electric field intensity at the holes' exit. However, taking into account the grid transparency, this increase in electroluminescence is partially cancelled out.

The maximum pressure at which the LAAPD can be safely operated is 2.5 bar. Therefore, the present studies were performed for gas filling pressures of 1, 1.5, 2.0, and 2.5 bar. The gas purity was maintained circulating the gas by convection through non-evaporable getters (SAES St707) heated up to about 140°C, being the gas at room temperature.

The GEMs used in this work had standard dimensions, i.e. a 50-μm Kapton foil with a 5-μm copper clad on both sides and bi-conical holes of 50- and 70-μm diameter in the Kapton and copper, respectively, arranged in a hexagonal layout with a 140-μm pitch. The THGEMs were made of standard printed circuit boards, a G-10 insulator clad with copper on both sides. The THGEM had a thickness of 0.4 mm, a 0.4-mm hole diameter with a copperless rim of 0.1 mm and a pitch of 0.8 mm. The GEM’s and THGEM’s active areas were 2.8 × 2.8 cm². The LAAPD had a 16-mm diameter active area. While for GEMs the copper-clad Kapton has a very low background radioactivity, of less than 30 μBq/cm² [22], standard THGEMs are made of G10 that contains glass fibres, having radioactive 40K. Therefore, other radio-clean materials such as Kevlar,
with around 0.4 mBq/cm² [23], or Cirlex, i.e. Kapton with larger thicknesses, should be used.

The LAAPD enclosure and the chamber were grounded, while the radiation window and the GEM’s (THGEM’s) top and bottom electrodes were biased independently. For the GEM, constant drift and induction fields of 0.5– and –0.1 kVcm⁻¹, respectively, were used throughout the measurements. For the THGEM, a constant drift field of 0.5 kV cm⁻¹ was used, while in the induction region electric fields between 2 and 4 kV cm⁻¹ were used throughout the measurements. An LAAPD bias voltage of 1840 V was used during all the measurements, corresponding to an LAAPD gain of around 130 [24,25].

A 1-mm diameter collimated 22.1-keV X-ray beam interacting in the drift region induces the production of primary electron clouds that are focused into the GEM or THGEM holes, where they undergo charge avalanche multiplication. For the GEM, a reversed electric field has been applied across the induction region to allow full collection of the avalanche electrons on the bottom electrode (anode) of the GEM, as shown in Fig. 1. For the THGEM, the avalanche electrons were chosen to be collected in the induction plane, i.e. a stainless steel mesh (80-μm wire diameter, 900-μm spacing) placed just above the LAAPD, Fig. 1. The latter configuration is the most used in the literature, for it decouples the amplification stage from the charge readout, with the advantage of using the most suitable readout pad for each application.

A large number of VUV scintillation photons are produced in the charge avalanche as a result of the gas de-excitation processes. A fraction of these photons reaches the LAAPD active area and the corresponding electric signal is amplified in the avalanche photodiode.

The electroluminescence amplification was defined by varying the voltage across the GEM’s or THGEM’s holes, where they undergo charge avalanche multiplication. For the GEM, a reversed electric field has been applied across the induction region to allow full collection of the avalanche electrons on the bottom electrode (anode) of the GEM, as shown in Fig. 1. For the THGEM, the avalanche electrons were chosen to be collected in the induction plane, i.e. a stainless steel mesh (80-μm wire diameter, 900-μm spacing) placed just above the LAAPD, Fig. 1. The latter configuration is the most used in the literature, for it decouples the amplification stage from the charge readout, with the advantage of using the most suitable readout pad for each application.

The electroluminescence yield can be directly obtained from

$$N_{UV} = \frac{A_X}{A_X} \times \frac{N_{e, XR}}{QE},$$

where $QE$ is the quantum efficiency of the LAAPD, defined as the number of charge carriers produced per incident VUV photon, being 1.1 for 172-nm photons and 0.55 for 128-nm photons [26,30]. The non-linear response of the LAAPD to 22.1-keV X-rays was taken into account and $A_X$ was corrected for this effect [31] with a factor of 1.1 for xenon and 1.12 for argon.

The absolute electroluminescence yield can be directly obtained from

$$Y = N_{UV} \times \frac{4\pi}{T \times \Omega_{sc}} \times \left( \frac{E_x}{w_{E_x}} \right)^{-1},$$

where $\Omega_{sc}$ is the solid angle subtended by the LAAPD, $E_x$ is the energy of the incident X-ray, $T$ is the mesh optical transparency and $w_{E_x}$, the respective $w$-value for the fill gas and for the X-ray energy $E_x$. In the present conditions, the $w$-value for xenon is 21.77 eV and for argon 26.4 eV, for 22.1-keV X-rays [32,33]. The relative solid angle subtended by the LAAPD is determined from the setup geometry, assuming the scintillation to be produced in the detector axis, is $\Omega_{sc}/4\pi = 0.28$ for the GEM geometry and $\Omega_{sc}/4\pi = 0.24$ for the THGEM geometry. The mesh optical transparency is 100% for the GEM setup and 84% for the THGEM setup. The dominating sources of uncertainty in the calculated yield are $QE$ and $\Omega_{sc}$, the values being estimated to be ±10% each.

This method is similar to that used for the determination of the absolute electroluminescence yield in argon and xenon for uniform electric fields [34,35].

4. Experimental results and discussion

In Fig. 2 we present the electroluminescence yield for GEMs (Fig. 2b and 2d) and THGEMs (Figs. 2a and 2c) operating in xenon and argon, as a function of voltage difference applied to the GEM/THGEM holes, for different gas pressures. The voltages were gradually increased, until a microdischarge in about every 2 to 3 minutes occurred. Taking into account the values for pressure, temperature, voltage difference applied to the scintillation gap and the thickness of the gap in XENON100 [8] and ZEPLIN-III [2] setups, values of 305 and 340 photons per primary electron have been determined for the respective electroluminescence yields [35]. Since there are no data in the literature for the amount of electroluminescence produced in the WARP detector, no comparison can be made with the present values. Nevertheless, the electroluminescence produced in argon in a 5-mm uniform field scintillation gap for a reduced electric field of 3.0 kV cm⁻¹ bar⁻¹, taken from [34], was included in Figs. 2c and 2d for comparison, and is represented by the horizontal solid lines.

The maximum achieved electroluminescence yield in xenon reaches very high values but presents, for the THGEM, a fast decrease with increasing pressure, from about $7 \times 10^4$ photons per primary electron, at 1 bar, to about $2 \times 10^3$ photons per primary electron, at 2.5 bar. Compared to the GEM, the THGEM electroluminescence yield decreases faster with xenon pressure; the electroluminescence yield achieved with THGEMs is one order of magnitude higher than those achieved in GEMs, at 1 bar, but presents already similar yields at 2.5 bar.
Fig. 2. Electroluminescence yield, \( Y \), i.e. number of photons produced in THGEMs (Figs. 2a and 2c) or GEMs (Figs. 2b and 2d) per primary electron produced in the drift region as a function of voltage applied to the THGEM or GEM holes operating in xenon and argon. The horizontal lines correspond to the electroluminescence produced in uniform field gaps in argon, for a 5-mm thick scintillation gap with a reduced electric field of 3.0 kV cm\(^{-1}\) bar\(^{-1}\), and in xenon, for the XENON 100 and ZEPLIN-III setups.

The electroluminescence is produced by the secondary electrons formed along the avalanche. The electron avalanche development in the GEM's and THGEM's holes is determined by the electron-impact mechanism [36], which explains the maximum gain-drop for higher pressures; the maximum applied voltage does not increase as fast as pressure, thus, the reduced electric field decreases with increasing pressure. The lower values of the reduced electric field in THGEMs result in a faster dependence of the Townsend coefficient on the reduced electric field.

When compared to what is achieved using a uniform electric field scintillation gap, the electroluminescence yields obtained in THGEMs are more than one order of magnitude higher, except for 2.5 bar, for which they are only four times higher. The xenon gas pressure in a dual-phase TPC at normal operation conditions depends on the detector configuration and on the temperature gradients. For gas pressures below 0.8 bar the liquid phase may condense. Therefore, under normal operation, the xenon pressure in the gas phase is kept above 1.1–1.2 bar (e.g. Refs. [18,37]) or even higher to have a safer margin for possible pressure fluctuations, e.g. around 1.6 bar [37]. These pressures correspond to a pressure range from 1.8 to 2.5 bar at 20\(^\circ\)C. In these cases, compared to a uniform field gap, the electroluminescence yield is a factor of 20 and 4 higher, respectively, for the THGEM case, and of 4 and 2 for the GEM.

For the THGEM and GEM operating in argon, the dependence of the maximum achieved yield with the gas pressure is much lower than for xenon, following the lesser dependence of the Townsend coefficient on the values of reduced electric fields present in those microstructures operated in argon; the charge avalanche gain reduction with increasing pressure is much more pronounced for GEM/THGEM operation in xenon than for their operation in argon.

For argon, the maximum EL yield achieved in THGEMs is about \(1.5 \times 10^4\) at 1 bar, reducing smoothly to about \(4 \times 10^3\) at 2.5 bar, while in GEMs the maximum achieved EL yield does not depend significantly on the pressure, being around \(3 \times 10^2\) photons per primary electron. The EL yield produced in GEMs is similar to that obtained in a uniform field scintillation gap. Therefore, in argon there is no advantage in using GEMs for scintillation amplification, in opposition to xenon. On the contrary, the scintillation produced in THGEMs operating in argon for 1 bar and 1.5 bar is two orders of magnitude higher than that produced in a 5-mm thick uniform field scintillation gap with a reduced electric field of 3.0 kV cm\(^{-1}\) bar\(^{-1}\), being still one order of magnitude higher at 2.5 bar. Therefore, the use of a THGEM as a mean to produce EL in argon-filled detectors may present advantages over the use of uniform electric field scintillation gaps. For an argon dual-phase TPC a pressure of almost 1 bar is planned [38], corresponding to a pressure of about 3.3 bar, for the same density, at 20\(^\circ\)C. Nevertheless, operation of a dual-phase TPC, for which the gas density corresponds to a pressure of 1 bar at 20\(^\circ\)C, has been reported in the literature [13,17].

The calibration of the electronic chain of the scintillation readout channel allows an independent determination of the EL yield. This calibration allows the calculation of the number of electrons collected in the LAAPD anode per primary electron produced in the...
Table 1: Maximum electroluminescence yields for GEMs, THGEMs and 5-mm thick uniform field gap.

|               | Xenon | Argon |
|---------------|-------|-------|
|               | 1 bar | 1.5 bar | 2 bar | 2.5 bar | 1 bar | 1.5 bar | 2 bar | 2.5 bar |
| GEM           | $6 \times 10^{3}$ | $3.4 \times 10^{3}$ | $1.5 \times 10^{3}$ | $1.2 \times 10^{3}$ | $2.7 \times 10^{2}$ | $4.8 \times 10^{2}$ | $4.4 \times 10^{2}$ | $3.3 \times 10^{2}$ |
| THGEM         | $7 \times 10^{4}$ | $1.3 \times 10^{4}$ | $8 \times 10^{3}$ | $2.2 \times 10^{3}$ | $1.5 \times 10^{4}$ | $7.8 \times 10^{3}$ | $3.9 \times 10^{3}$ | $3.8 \times 10^{3}$ |
| 5-mm uniform field gap' | $2.2 \times 10^{2}$ | $3.3 \times 10^{2}$ | $4.4 \times 10^{2}$ | $5.5 \times 10^{2}$ | $1.0 \times 10^{2}$ | $1.5 \times 10^{2}$ | $2.0 \times 10^{2}$ | $2.5 \times 10^{2}$ |

* Xenon: $E/p = 4.0$ kV cm$^{-1}$ bar$^{-1}$, argon: $E/p = 3.0$ kV cm$^{-1}$ bar$^{-1}$.

The values calculated from Eq. (4) are similar to those obtained with the former method, within less than 20% for xenon and within 30% for argon. However, the uncertainty in the yield obtained by this last method is higher because of the uncertainty in $G_{APD}$ and in $G_{tot}$, which are larger than that of $QE$.

5. Conclusions

The electroluminescence yield, defined as the number of photons produced in the electron avalanches per primary electron resulting from the radiation interaction in the gas, has been determined for GEM and THGEM electron multipliers. These studies are important for the correct simulation of the EL-based TPCs containing these microstructures and to be used as a benchmark for the avalanche gains and, therefore, electroluminescence gains that are achievable at room temperature. These studies are ongoing since the last few years [13,15–18,28,39] and steady progress is being achieved.

The ultimate goal for a simplified detector would be reading out the primary ionisation charge by means of charge avalanche amplification processes (preferably in the liquid), avoiding the use of photosensors. Therefore, there are groups doing R&D in that direction [40–45]. However, as also referred in [46–49], we advocate that charge avalanche readout result in feeble signals with much lower amplitudes than those of scintillation signals. In xenon, the avalanche gains achieved in GEMs and THGEMs at xenon pressures around 2 bar are only of a few hundred electrons per primary electron [13,16], too few to obtain a clean signal considering the small energies deposited in the detector by xenon recoils.

According to our measurements, for xenon, the signal amplitudes obtained from the readout of the scintillation produced in GEM and THGEM avalanches, using an LAAPD as a photosensor, are more than two orders of magnitude higher than those obtained from direct readout of the avalanche charge, for the whole pressure range studied. For the argon case, the above ratio is one order of magnitude.

Acknowledgements

Financial support is acknowledged from FEDER and FCT, Lisbon, under COMPETE program, through project PTDC/FIS/103860/2008. C.M.B. Monteiro acknowledges grant SFRH/BPD/76842/2011 from FCT, Lisbon and European Social Fund.

References

[1] E. Aprile, et al., XENON10 Collaboration, Phys. Rev. Lett. 107 (2011) 131302, arXiv:1104.2549v2.
[2] D.Yu. Akimov, G.J. Alner, H.M. Araujo, A. Bewick, C. Bungau, et al., Astropart. Phys. 27 (2007) 46.
[3] M. Seydagis, LUX Design, Calibration, and Simulation, “TIPP 2011- Technology and Instrumentation in Particle Physics”, Chicago, USA, June 17, 2011.
[4] P. Benetti, F. Calaprice, E. Calligaris, M. Cambiaghi, F. Carbonara, et al., WARP Collaboration, Astropart. Phys. 28 (2008) 495.
[5] D. Nygren, Nucl. Instr. Meth. A 601 (2009) 337.
[6] V. Álvarez, M. Ball, M. Batalié, J. Bayarri, F.L.G. Borges, et al., NEXT Collaboration, arXiv:1106.3630 [physics.ins-det].
[7] D. Sinclair, EXO Collaboration, J. Phys. Conf. Ser. 203 (2010) 012062.
[8] E. Aprile, et al., XENON100 Collaboration, Astropart. Phys. 35 (2012) 573.
[9] C.M.B. Monteiro, A.S. Conceição, F.D. Amaro, J.M. Maia, A.C.S.S.M. Bento, et al., Phys. Lett. B 677 (2009) 133.
[10] E. Aprile, et al., XENON100 Collaboration, Astropart. Phys. 35 (2011) 43.
[11] D.S. Leonard, et al., EXO Collaboration, Nucl. Instr. Meth. A 591 (2008) 490.
[12] C. Rutter, M. Richards, A.J. Benninston, Y.A. Ramachers, JINST 6 (2011) P07006.
[13] A. Buzulutskov, JINST 7 (2012) CD0205, arXiv:1112.6153, and references therein.
[14] A. Breskin, R. Alon, M. Cortesi, R. Chechik, J. Miyamoto, et al., Nucl. Instr. Meth. A 598 (2009) 107.
[15] P.K. Lightfoot, C.J. Barker, K. Mavrokorides, Y.A. Ramachers, N.J.C. Spooner, JINST 4 (2009) P04002.
[16] D.Yu. Akimov, A.V. Akimov, I.S. Alexandrov, A.A. Burenkov, M.V. Danilov, et al., JINST 5 (2010) P04007.
[17] A. Bondar, A. Buzulutskov, A. Grebenuk, A. Sokolov, D. Akimov, et al., JINST 5 (2010) P08002.
[18] A. Bondar, A. Buzulutskov, A. Grebenuk, E. Shemyakina, A. Sokolov, et al., JINST 6 (2011) P07008.
[19] F. Sauli, Nucl. Instr. Meth. A 386 (1997) 531.
[20] J.M. Maia, J.F.C.A. Veloso, J.M.F. dos Santos, A. Breskin, R. Chechik, et al., Nucl. Instr. Meth. A 504 (2003) 364.
[21] C.A.B. Oliveira, H. Schindler, R. Veenhof, S. Biagi, C.M.B. Monteiro, et al., Phys. Lett. B 703 (2011) 217.
[22] S. Cebrian, T. Dafni, E. Ferrer-Ribas, J. Galán, I. Giomataris, et al., Astropart. Phys. 34 (2011) 354.
[23] ILIAS Database in: Radiopurity of Materials, http://radiopurity.in2p3.fr, 2008.
[24] C.M.B. Monteiro, J.A.M. Lopes, P.C.P.S. Simões, J.M.F. dos Santos, C.A.N. Conde, IEEE Trans. Nucl. Sci. 48 (2001) 1081.
[25] J.A.M. Lopes, J.M.F. Dos Santos, R.E. Morgado, C.A.N. Conde, IEEE Trans. Nucl. Sci. 48 (2001) 312.
[26] M. Suzuki, S. Kubota, Nucl. Instr. Meth. 164 (1979) 197.
[27] M.M. Fraga, F.A.F. Fraga, A.J.P.L. Policarpo, Nucl. Instr. Meth. A 442 (2000) 423.
[28] A. Buzulutskov, A. Bondar, A. Grebenik, Europhys. Lett. 94 (2011) 52001, arXiv:1102.1825.
[29] G.F. Knoll, Radiation Detection and Measurement, 4th edition, Wiley, New York, 2010.
[30] B. Zhou, M. Szawolski, An Explanation on the APD Spectral Quantum Efficiency in the Deep UV Range, Interoffice Memo, Advanced Photonix Inc., 1240 Avenida Acaso, Camarillo, CA 93012, USA, 1999.
[31] L.M.P. Fernandes, J.A.M. Lopes, C.M.B. Monteiro, J.M.F. dos Santos, C.A.N. Conde, Nucl. Instr. Meth. A 478 (2002) 395.
[32] T.H.V.T. Dias, J.M.F. dos Santos, P.J.B.M. Rachinhas, F.P. Santos, C.A.N. Conde, et al., J. Appl. Phys. 82 (1997) 2742.
[33] LK. Bronic, Hoshasen: ionizing radiation, vol. 24, 1998, p. 101.
[34] C.M.B. Monteiro, J.F.C.A. Veloso, J.A.M. Lopes, J.M.F. dos Santos, Phys. Lett. B 668 (2008) 167.
[35] C.M.B. Monteiro, L.M.P. Fernandes, J.A.M. Lopes, L.C.C. Coelho, J.F.C.A. Veloso, et al., JINST 2 (2007) P05001.
[36] A. Buzulutskov, Nucl. Instr. Meth. A 494 (2002) 148, and references therein.
[37] H. Araújo, UCLA DARK MATTER 2012, Tenth Symposium on Sources and Detection of Dark Matter in the Universe, Marina del Rey, USA, February 22–24, 2012, https://hepconf.physics.ucla.edu/dm12/talks/araujo.pdf.
[38] A. Rubbia, J. Phys. Conf. Ser. 171 (2009) 012020.
[39] C. Amsler, A. Badertscher, V. Bochene, A. Bueno, et al., JINST 5 (2010) P11003.
[40] A. Rubbia, J. Phys. Conf. Ser. 39 (2006) 129.
[41] P.K. Lightfoot, N.J.C. Spooner, T.B. Lawson, S. Aune, et al., Astropart. Phys. 27 (2007) 490.
[42] M. Gai, D.N. McKinsey, K. Ni, D.A.R. Rubin, T. Wongjirad, et al., arXiv:0706.1106v1 [physics.ins-det], vol. 8, June 2007.
[43] F. Balau, V. Solovov, V. Chepel, A. Pereira, et al., Nucl. Instr. Meth. A 598 (2009) 126.
[44] A. Menegolli, ICARUS Collaboration, J. Phys. Conf. Ser. 203 (2010) 012107.
[45] B. Baibussinov, M. Baldo Ceolin (1), G. Battistoni (2), P. Benetti, et al., Astropart. Phys. 29 (2008) 174.
[46] D. Autiero, J. Aysto, A. Badertscher, L. Bezrukov, et al., J. Cosmol. Astropart. Phys. 11 (2007) 011.
[47] P.K. Lightfoot, G.J. Baker, K. Mavrokoridis, Y.A. Ramachers, N.J.C. Spooner, JINST 4 (2009) P04002.
[48] A. Marchionni, arXiv:0912.4417.
[49] D.Y. Stewart, G.J. Barker, A.J. Bennieston, P.F. Harrison, et al., JINST 5 (2010) P10005.