ELECTRON MULTIPLICATION AND SECONDARY SCINTILLATION IN LIQUID XENON: NEW PROSPECTS

A.J.P.L.Policarpo, V.Chepel, M.I.Lopes and R.Ferreira Marques
LIP-Coimbra and Physics Department of the University of Coimbra
University of Coimbra, 3000 Coimbra, Portugal

ABSTRACT

The history, present situation and prospects on electron multiplication and secondary scintillation in liquid xenon and their application to radiation detectors are shortly discussed.

1 Introduction

Proportional charge multiplication and secondary scintillation are two effects of great importance for radiation detection. Intrinsic amplification in a detector, which becomes possible thanks to these mechanisms, notably improves the detector performance. Apart from reducing requirements to the front end electronics, the intrinsic amplification results in significant increase of signal-to-noise ratio and, as a consequence, allows the detection of particles that deposit in the detector very low energy with good energy resolution. Moreover, the influence of positive ions, produced by an ionizing particle along its track, on the signal amplitude can be neglected. The essence of proportional multiplication is that electrons, drifting in a strong electric field, gain enough energy to ionize the atoms and/or molecules of the medium. Overall, every primary electron can produce thousands of secondary electrons. Thus, yielding a total collected charge at the detector output proportional to the ionization charge (energy deposit) produced by the incoming particle.

Typically, the practical electric field threshold for achieving charge multiplication in gas is E/p^a~5 to 10 V/cm/Torr (E/N >1.4x10^{-16} Vcm^2), where E is the electric field strength, N the number of atoms/molecules of the gas per cubic centimeter and p the pressure.

Secondary scintillation does not require such a high field as charge multiplication of the charge as the drifting electrons do not ionize the gas but just excite its atoms. The threshold field for secondary scintillation in noble gases is about E/p~1 V/cm/Torr (E/N~3x10^{-17} Vcm^2). The scintillation light, mostly UV or VUV, emitted is commonly detected by photomultiplier tubes. One drifting electron can produce up to hundreds of

photons reaching the photomultiplier, resulting in tens to hundreds of photoelectrons emitted from the photocathode. Employing the secondary scintillation allows very good energy resolution to be achieved as the statistics of charge multiplication is avoided.

In general, excitation of the gas by drifting electrons always precedes charge multiplication. In proportional counters, however, the light emission plays a negative role. It may give rise to electric discharges due to possible photoelectric emission of electrons at the cathode thus resulting in positive feedback in the chamber. Therefore, quenching admixtures are usually added to the main detecting gas, in order to suppress the light emission or shorten its mean free path, thus allowing to achieve higher charge gains. For example, in gaseous xenon, which is the most efficient g-ray absorber, an order of magnitude higher gain can be achieved with Xe/CH_4 mixture than with pure xenon [1]. Conversely, employing secondary scintillation requires the gas to be pure. It is very important to keep in mind this point when one considers the possibility of electron multiplication or secondary scintillation in liquid xenon as the purity requirements in the liquid are much more severe than in the gas. Concentration of electronegative impurities of ~10 ppb (oxygen equivalent) limits the electron life time to a few ms and is not acceptable for many applications.

Liquid xenon detectors were recently proposed for various applications: as electromagnetic calorimeters for high energy physics [2,3], for gamma ray detection in astronomy [4], as a time projection chamber for particle physics experiments [5], imaging detectors for nuclear medicine [6,7]. These detectors work either in ionization or in primary scintillation mode or combine both of them, i.e. with no intrinsic amplification in the chamber. However, even a moderate charge amplification is highly desirable. This justifies the efforts that were and are being made in order to study the possibility of achieving both multiplication and secondary scintillation in liquid xenon detectors, which is the subject we shall discuss below.

2 Historical survey

The first observations of the electron multiplication in condensed noble gases were reported 50 years ago by Hutchinson [8]. Twenty years later, in the beginning of the 70s, a detail investigation of multiplication in liquid xenon in view of possible applications for radiation detection was initiated by L.W.Alvarez and carried out independently in several laboratories [9-12]. The ultimate goal of replacing the gas in the proportional chamber with a liquefied noble gas was to improve the position resolution. Indeed, increasing the density of the detecting medium would result in an increase of the number of ion pairs produced by a minimum ionizing particle within the detector, thus allowing a more accurate definition of

the center of gravity of the electron distribution and, therefore, better localization. In addition, this is accompanied by the suppression of electron diffusion and delta-ray range. Furthermore, the decrease of the detector thickness decreases the localization uncertainty due to parallax. Alternatively, sacrificing spatial resolution, a thick chamber can be produced providing high detection efficiency of g-rays.

A maximum gain of about 200 has been obtained in a liquid xenon single wire cylindrical proportional chamber with very thin anode wires using as a radioactive source either an internal ^{207}Bi, which emits conversion electrons and g-rays of energy of about 0.5 MeV and 1 MeV, or an external g-ray source ^{137}Cs (662 keV) or ^{207}Hg (85 keV and 279 keV). It was found that multiplication in the liquid occurs at E/N significantly lower than one could expect from a simple extrapolation of the data obtained in gaseous xenon to the liquid densities. Nevertheless, wires of 3 to 5 mm diameter are required to obtain electric field strengths of ~1 MV/cm near the anode surface at the applied voltage of several kV. An energy resolution of about 22%, fwhm, was measured for 279 keV g-rays with the 3.5 mm wire at gain of 10 [10]. The resolution becomes worse at higher gains. A poor energy resolution roots, apparently, in the non-uniformity of the wire diameter and probable irregularities on its surface (one can roughly estimate that variations of the diameter of 1% can cause differences in the gain of ~30%).

Chambers of 6 to 10 mm cathode diameter were experimented by different authors [9-12]. A saturation of the charge pulse amplitude after reaching a gain of ~200 due to accumulation of positive space charge near the wire was observed. For example, a reduction of the count rate from 2000 to 200 s^{-1} resulted in an increase of the saturation amplitude by a factor of 3 [10] (for the cathode diameter of 8 mm), showing that the low mobility of positive ions in liquid xenon constitutes a real problem for the practical use of the electron multiplication.

The first Townsend coefficient, a, was computed by fitting the experimental data with 9 adjusting parameters [10]. It was found to be 27 times larger than it would be in gaseous xenon with the same density showing that liquid xenon is not just a compressed gas. The maximum reported value of $a=(4.47\pm0.26)\times10^4$ cm^{-1} was obtained at E=2 MV/cm. The results were, however, questioned by T.Doke, since the fit does not converge to the right W-value and recombination constant [13]. The coefficient a was also derived by Prunier et al. [11] from independent measurements. The values reported were close to those obtained by Derenzo et al. at fields above ~0.8 MV/cm, but the W-value suffers from the same inconsistency with other data.

An attempt to build a multiwire proportional chamber has been undertaken [14]. However, much higher voltages were required to reach the same gain as in a single wire counter and, practically, it was difficult to operate the chamber at a gain higher than 10.

Such thin wires are very difficult to handle; they can be easily damaged by electrical discharges. In addition, the electrostatic repulsion between the wires in a multiwire chamber is so strong that frequently leads to breaking the wires, just due to application of a high voltage, and special means (wires interlaced with quartz fibers) were necessary to keep the wires in a plane. Thus, although the first results were very promising and significant and reproducible multiplication of electrons in liquid xenon has been obtained, the technical difficulties associated to practical applications are such that this line of research was practically abandoned.

Secondary scintillation of liquid xenon has been first observed by Dolgoshein et al. [15] in a uniform electric field. The threshold field was found to be ~100 kV/cm. Later, it was studied by a Japanese group [16, 17] in a cylindrical geometry with wires of 4 to 20 mm diameter. Although, the authors do not present the absolute number of photons emitted, one can roughly estimate it to be ~10 to ~100 photons per primary electron, depending on the applied voltage, for the 4 mm anode wire. The lowest value corresponds to a voltage at which there is essentially no charge multiplication while the highest one was obtained for a charge gain of ~50 was observed.

Assuming the same linear relationship between the number of photons per electron and the electric field strength, found for gas, the authors made a fit to the measured data and found the threshold field for secondary scintillation in liquid xenon to be surprisingly high. A value ranging from 400 kV/cm to 700 kV/cm was derived, which is much larger than the one previously obtained [15] and very close to the field at which the electron multiplication occurs. However, these figures are consistent with the value calculated considering liquid xenon as compressed gas at 520 bar.

Proportional scintillation could also be observed with thicker wires. With the wire of 20 mm diameter, ~5 photons per electron are emitted at an anode voltage of 5 kV, as estimated by T.Doke [18] (our estimate, using the same method as above and taking into account the scintillation light yield for liquid xenon measured in [19], gives the value of ~20 photons per primary electron). For a 50 mm wire, the figure of ª30 photons per electron was estimated to be achievable at the anode voltage of 12 kV [20].

However, the energy resolution as good as expected has not been obtained. It was measured to be about 16-20% for 1 MeV electrons, almost independently of the wire diameter [16]. The same 16% resolution was also obtained when the chamber was operated in ionization mode. The authors attribute this fact to imperfect charge collection onto the

wire in that particular chamber geometry. In a better geometry, the resolution of 15% was measured for alpha-particles [17]. In order to compare this value to that obtained with electrons, one should take into account that due to high ionization density along the alpha-particle track in liquid xenon, only a few percent of the electrons escape the recombination in the field of ~10 kV/cm. Thus, the number of electrons collected onto the anode wire in this experiment corresponds to an energy deposition of ~250 keV by a minimum ionizing particle. To our knowledge, there are no other experimental results published in the literature showing that a better energy resolution has be achieved.

Secondary scintillation was used in a liquid xenon drift chamber built for precise localization of charged particles (20 mm, r.m.s.) [17] or annihilation g-rays (0.9 mm, fwhm) [21]. Recently, a liquid xenon detector was developed for detection of WIMP's (Weak Interacting Massive Particles) [22]. Detection of the xenon primary and secondary scintillation from the same event allows to discriminate the background, mainly due to minimum ionizing particles, and to detect the recoil nuclei with high signal-to-noise ratio. Secondary scintillation, with an increase in the photon yield relatively to the primary scintillation by a factor of 10 (for 122 keV g-rays; 4.5 mm wire), was measured and the information obtained allowed the design of a prototype of a 700 cm^3 chamber. To our knowledge, this is the first reasonably sized device designed with the specific aim of using intrinsic gains with liquid xenon, towards a well defined physics experiment.

3 Charge multiplication with new microstructures

The development of new microstructures, such as microstrip and microgap chambers, refreshed the interest for electron multiplication in liquid xenon. Indeed, not only such devices can be made with anode strips of several micrometers width and thus substitute thin fragile wires, but also the short anode to cathode distance allows the fast collection of positive ions. It is interesting to note that the advantage of such a kind of device was recognized more than 20 years ago: the "development of a practical high-resolution chamber of large size requires replacement of the stretched fine wires by conductive strips laid down on an insulating substrate" [9].

The electron multiplication in a microstrip plate (MS) has been observed in liquid xenon by us and is reported in the literature [23]. A plate of ILL-6C type was used for the measurements. It has anode strips of 8 mm width, cathodes of 400 mm width and 1000 mm anode pitch. The strips, made of nickel, are deposited on Desag D236 glass (Fig.1). An ^{241}Am alpha-source of 4 mm diameter was deposited on the drift electrode 1.9 mm away from the MS plate surface and parallel to it. All the anode strips were connected together, as well as all the cathodes. The negative voltage was applied to the drift electrode; cathodes were kept at the ground potential and a positive voltage applied to the anodes. Three signals were read from the chamber with low-noise charge-sensitive preamplifiers: at the anode strips, at the cathodes and at the drift electrode. The latter allowed to account for the recombination along the alpha-particle track which is a function of the drift field strength.

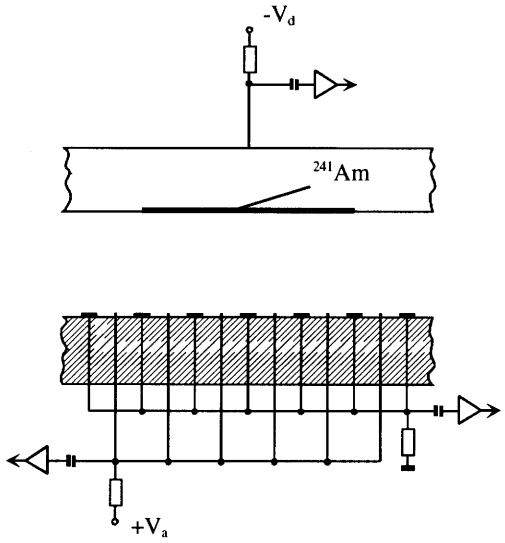

Fig.1 Schematic drawing of the liquid xenon chamber with a microstrip plate

The chamber was filled with carefully purified liquid xenon and cooled down to the temperature of about -60ºC being immersed into an ethanol bath cooled with liquid nitrogen.

With an increase of the anode voltage above 600 V (at constant drift voltage), the amplitude of the anode signals, normalized to those taken at the drift electrode (i.e., corrected for the charge yield from the particle track), started to rise while the signals at the cathode strips changes the polarity (Fig.2). The amplitude of the signals was determined as the position of the corresponding peak on the amplitude spectrum.

The interpretation of this plot is as follows. As the alpha-particle range in liquid xenon is of the order of tens of microns and the drifting electron cloud is broadened due to diffusion by ~100 mm, i.e. comparable with the distance between the cathode edge and the anode, and the source diameter is larger than the MS plate pitch, two possibilities may arise at low fields. First, the electrons extracted from each track can be collected almost totally either to the cathodes or to the anode strips, thus inducing negative charge signals with the amplitude equal to 1 (inverted in Fig.2) on the corresponding electrode. Second, the drifting charge can be split between the electrodes and this is the case for the anode potential <200 V at which the amplitude of the anode signal varies with the applied

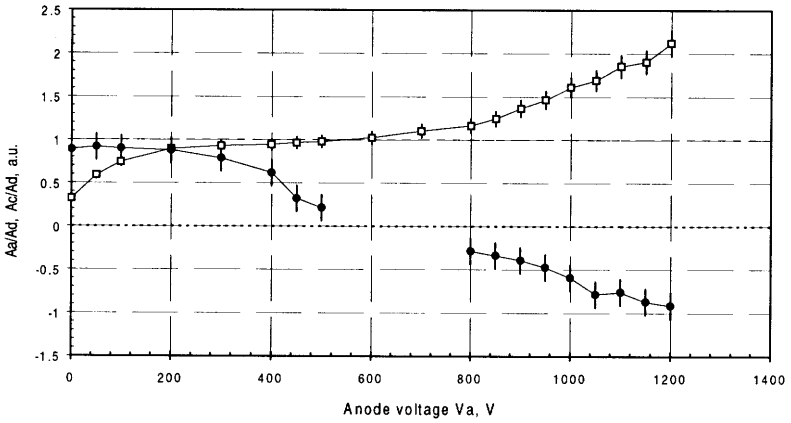

Fig.2 Anode and cathode signal amplitudes as a function of anode voltage [23].

Published with permission

voltage. An increase of the anode potential to 500 V results in complete charge collection to the anodes; the count rate at the anodes also increases at the cost of that observed at the cathodes; when the drifting charge is split, most of it is collected onto the anode strips, also yielding a decrease of the amplitude of the cathode signals. Up to this voltage, the results are fully explainable on the basis of collection conditions of the drifting electrons.

As one increases the anode voltage above 600 V, the electron multiplication starts. We observe both an exponential rise of the anode amplitude and the appearance of inverted pulses on the cathodes, induced by positive ions created near the anode surface and drifting towards the cathodes. The inequality of the amplitudes of the signals observed at the anodes and cathodes is, apparently, due to the long ion drift time estimated to be ~100 ms for the distance of 300 mm. Such long signals could not be measured correctly with our electronics. At the intermediate anode voltages, between 500 and 800 V, the signals of both polarities at the cathode strips could be observed with an oscilloscope, some of them

related with the collection of the electrons from the particle track to the cathodes while others being induced by those collected to the anode where the multiplication occurred.

At higher drift voltage, higher maximum multiplication gain could be achieved. At -2600 V applied to the drift electrode, we measured the gain of about 10 at the anode voltage of 1700 V. It was the highest voltage that we could apply to the anode. Further voltage increase resulted in unstable behavior and discharges.

The collection time of the positive ions in the MS chamber filled with liquid xenon is still long. It can be eventually reduced several times by using a plate with smaller distance between the anode and cathode strips. A more radical solution is to use a microgap chamber (MGC) instead. In this chamber, the anode strips are separated from the cathode plane by a thin insulating layer so that the drift path of the ions can be made of a few microns. In addition, a higher field strength at the anode surface is expected to be achieved at lower anode voltage. Therefore, we also experimented an MGC chamber produced in Delft Technical University [24] in liquid xenon. The experimental set-up and working conditions were essentially the same as for the MS chamber. However, discharges at anode voltage as low as 450 V did not allow to achieve the field strength at which the electron multiplication might possibly occur.

The MS plates and MGC chambers, in general advantageous when compared to wire chambers, have however one drawback: the existence of a dielectric surface supporting the electrodes significantly limits the operating voltage as it favors the occurrence of surface discharges. One could think about producing a substrate with a special profile in order to reduce the tangential component of the electric field at the dielectric surface (the leak microstructure [25] is an example) but it complicates the design and such a device can become too “bulky” for some applications (this is the case of the liquid xenon detector for PET, for instance [7], where the dead volume in the chamber has to be minimized).

A new microstructure, the so called “virtual cathode chamber”, which has recently been suggested for gas filled proportional detectors [26], may be an interesting option for a liquid xenon detector, as well. It attracts by the simplicity of the design and by having a bulk insulator (substrate) between the anode strips and the cathode layer deposited on the opposite side of the substrate (Fig.3) thus avoiding discharges.

In order to assess the possibility of charge multiplication with this device, we performed calculations of the electric field and the multiplication gain for the chamber shown in fig.3 and for various sets of potentials at the drift electrode and the cathode plane, assuming the anode strips to be kept at the ground potential. The field configuration obtained for V_d= -2000 V and V_c= -1800 V is shown in Fig.4. The calculations show that the field strength of >1 MV/cm, necessary for multiplication in liquid xenon, can be

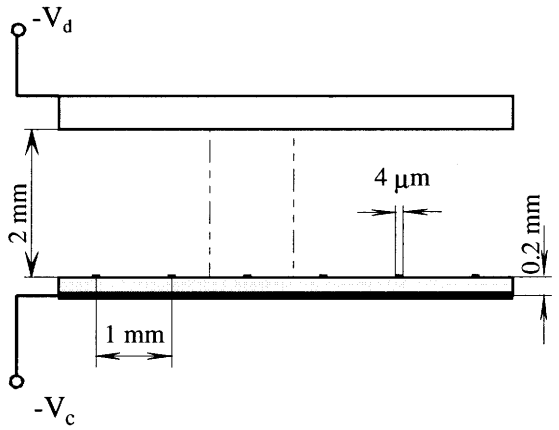

Fig.3 Virtual cathode chamber configuration considered in calculations. Selected central area corresponds to that shown in Fig.4.

achieved along a few mm close to the surface of the anode strip. Moreover, near the anode, the field varies with the distance much slower than ~1/*r*, typical of cylindrical geometry, thus being more favorable for the multiplication. We have found that the multiplication region of several micrometers is expected to result into a total gain of ~100 or higher. However, one should remember that since the multiplication is an exponential process, a small uncertainty in the first Townsend coefficient, which we took from [10], may lead to a significant error in the calculated gain. Nevertheless, even being pessimistic we believe that the considered microstructure has good prospects in what concerns both charge multiplication and secondary scintillation.

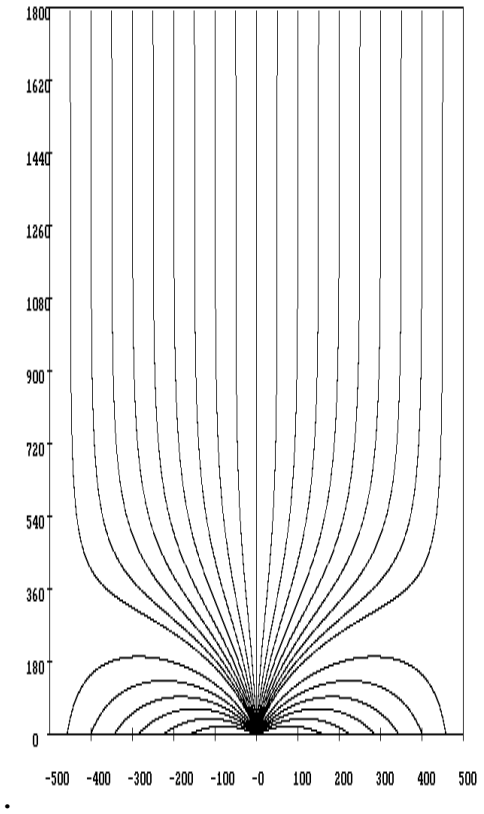

Fig.4 Field configuration in the drift region of the virtual cathode chamber shown in fig.3 with V_d= -1800 V and - V_d= -2000 V. Dimensions shown in the figure are in mm.

4 Conclusion

The possibility of taking profit from electron multiplication and secondary scintillation in liquid xenon radiation detectors, that were observed over 20 years ago and, at that time, did not find any practical applications due to technical difficulties, should be reconsidered, in view of the recent development of new reliable and easy to handle microstructures. The existing data, however, are contradictory and, therefore, additional studies of the multiplication and secondary scintillation processes are required.

References

[1] H.Sakurai and B.D.Ramsey. Dependence of Energy Resolution on Anode Diameter in Xenon Proportional Counters, *Nucl.Instr. and Meth. in Phys. Res.*, vol.A313, pp.155-160, 1992.

[2] J.Séguinot, G.Passardi, J.Tischhauser and T.Ypsilantis, Liquid Xenon Ionization and Scintillation. Studies for a Totally Active-Vector Electromagnetic Calorimeter, *Nucl. Instr. and Meth. in Phys. Res.*, vol.A323, pp.583-600, 1992.

[3] M.Chen, M.Mullins, D.Pelly et al. Homogeneous Scintillating LKr/LXe Calorimeters, *Nucl. Instr. and Meth. in Phys. Res.,* vol.A327, pp.187-192, 1993.

[4] E.Aprile and M.Suzuki, Development of Liquid Xenon Detectors for Gamma Ray Astronomy, *IEEE Trans. on Nucl. Sci.,* vol.NS-36, pp.311-315, 1989.

[5] G. Carugno, G.Pete, S.Cerdonio et al. Test of a Self Triggered Liquid Xenon TPC, Proc. Int. Conf. on Liquid Radiation Detectors, Waseda University, Tokyo, 1992, Ed. T.Doke, pp.104-108.

[6]V.V.Egorov,V.P.Miroshnichenko, B.U.Rodionov, A.I.Bolozdynya, S.D.Kalashnikov and V.L.Krivoshein. Electroluminescence Emission Gamma-Camera, *Nucl. Instr. and Meth.,* vol.205, pp.373-374, 1983.

[7] V.Yu.Chepel, M.I.Lopes, H.M.Araújo, M.A.Alves, R.Ferreira Marques and A.J.P.L.Policarpo. Liquid Xenon Multiwire Chamber for Positron Tomography, *Nucl. Instr. and Meth. in Phys. Res.,* vol.A367, pp.58-61, 1995.

[8] G.W.Hutchinson. Ionization in Liquid and Solid Argon, *Nature*, vol.162, pp.610-611, 1948.

[9] R.A.Muller, S.E.Derenzo, G.Smadja, D.B.Smith, R.G.Smits, H.Zaklad and L.W.Alvarez. Liquid-Filled Proportional Counter, *Phys. Rev. Lett.*, vol.27, pp.532-535, 1971.

[10] S.E.Derenzo, T.S.Mast, H.Zaklad and R.A.Muller. Electron Avalanche in Liquid Xenon, *Phys. Rev.*, vol.A9, pp.2582-2591, 1974.

[11] J.Prunier, R.Allemand, M.Laval and G.Thomas. Some Properties of Xenon Liquid-Filled Nuclear Detectors, *Nucl. Instr. and Meth.*, vol.109, pp.257-264, 1973.

[12] M.Miyajima, K.Masuda, A.Hitachi, T.Doke, T.Takahashi, S.Konno, T.Hamada, S.Kubota, A.Nakamoto and E.Shibamura. Proportional Counter Filled With Highly Purified Liquid Xenon, *Nucl.Instr. and Meth.,* vol.134, pp.403-405, 1976.

[13] T.Doke. Fundamental Properties of Liquid Argon, Krypton and Xenon as Radiation Detector Media, *Portug. Phys.*, vol.12, pp.9-48, 1981.

[14] H.Zaklad, S.E.Derenzo, R.A.Muller and R.G.Smits. Initial Images From a 24-Wire Liquid Xenon g-Camera, *IEEE Trans. Nucl. Sci.*, vol.NS-20, pp.429-431, 1973

[15] B.A.Dolgoshein, V.N.Lebedenko and B.U.Rodionov. Luminescence Induced by Alpha Particles in Liquid Xenon in an Electric Field, *JETP Lett.*, vol.6, p.224, 1967.

[16] K.Masuda, S.Takasu, T.Doke, T.Takahashi, A.Nakamoto, S.Kubota and E.Shibamura. A Liquid Xenon Proportional Scintillation Counter, *Nucl.Instr. and Meth.,* vol.160, pp.247-253, 1979.

[17] M.Miyajima, K.Masuda, Y.Hoshi, T.Doke, T.Takahashi, T.Hamada, S.Kubota, A.Nakamoto and E.Shibamura. A Self-Triggered Liquid Xenon Drift Chamber by the

Use of Proportional Ionisation or Proportional Scintillation, *Nucl.Instr. and Meth.*, vol.160, pp.239-246, 1979.

[18] T.Doke. Recent Developments of Liquid Xenon Detectors, *Nucl.Instr. and Meth.*, vol.196, pp.87-96, 1982

[19] M.Miyajima, S.Sasaki and E.Shibamura. Absolute Number of Photons Produced by Alpha-particles in Liquid and Gaseous Xenon, , *Nucl. Instr. and Meth. in Phys. Res.*, vol.B63, pp.297-308, 1992.

[20] A.J.P.L.Policarpo. Ionization Scintillation Detectors, *Nucl. Instr. and Meth.*, vol.196, pp.53-62, 1982.

[21] K.Masuda, T.Doke and T.Takahashi. A Liquid Xenon Position Sensitive Gamma-Ray Detector for Positron Annihilation Experiments, *Nucl.Instr. and Meth.*, vol.188, pp.629-638, 1981.

[22] P.Benetti, E.Calligarich, R.Dolfini et al., Detection of Energy Deposition down to the keV Region Using Liquid Xenon Scintillation, *Nucl. Instr. and Meth. in Phys. Res.*, vol.A327, pp.203-206, 1993.

[23] A.J.P.L.Policarpo, V.Chepel, M.I.Lopes et al. Observation of Electron Multiplication in Liquid Xenon with a Microstrip Plate, *Nucl. Instr. and Meth. in Phys. Res.*, vol.A365, pp.568-571, 1995.

[24] J. van der Marel, A. van den Bogaard, C.W.E. van Eijk, R.W.Hollander and P.M.Sarro. Two-Dimensional Microgap Gas Chambers on Silicon, *Nucl. Instr. and Meth. in Phys. Res.*, vol.A367, pp.181-184, 1995.

[25] M.Lombardi and F.S.Lombardi. The Leak Microstructure, Preliminary Results, *Nucl. Instr. and Meth. in Phys. Res.*, vol.A367, pp.23-27, 1995.

[26] M.Capeáns, W.Dominik, M.Hoch, L.Ropelewski, F.Sauli, L.Shekhtman, A.Sharma. The Virtual Cathode Camber, Preprint CERN-PPE/97-61.