

Liquid Rare Gas Detectors: Recent Developments and Applications

M. I. Lopes and V. Chepel

LIP—Laboratório de Instrumentação e Física Experimental de Partículas
C.F.R.M. de Departamento de Física, Universidade de Coimbra
3004-516 Coimbra, Portugal

ABSTRACT

In past years, liquid rare gas detectors (LRGD) have made a considerable progress and found application in various fields of research, such as high energy experiments, astrophysics, search for rare processes and medical imaging. This review paper starts by a short summary and discussion of the properties of liquid rare gases (LRG) that make them attractive as radiation detector media. Next, the two best-established technologies based on liquid rare gases, electromagnetic calorimeters and time projection chambers, are briefly reviewed along with their main applications. The bulk of the paper is focused on the challenging development of LRGD for the search of rare processes in low background experiments with an emphasis on those dealing with the direct detection of dark matter. The challenges posed by those experiments, the detectors proposed and their present status of development are described. A brief review of the proposals of using LRGD for medical imaging is outlined and the present status of some of the more significant developments under way is presented.

Index Terms — Liquid xenon, liquid argon, liquid krypton, particle detectors, liquid rare gases, gamma-ray detectors, radiation detectors, liquid detectors, dielectric liquids.

1 INTRODUCTION

A GREAT progress has been achieved in the development of liquid rare gas detectors (LRGD) since liquid argon was suggested as detector medium for ionization chambers ([1] and references therein) and, especially, since a liquid argon sampling calorimeter for a high energy physics experiment was built in 1974 [2].

Systematic studies of the fundamental properties of liquid rare gases (LRG) have been carried out allowing a better understanding of the potentialities and limiting factors of the detectors based on such liquids ([3,4] and references therein). Technical difficulties, like the reduction of the concentration of electronegative and scintillation photon absorbing impurities down to the level of ~ 1 ppb (parts per billion) and the maintenance of this level of purity for long periods of time, were overcome after more than two decades of intensive efforts [5–10].

Different types of LRGD have been proposed and developed for a great variety of applications. It is beyond the scope of this paper to review all these devices and appli-

cations. Therefore, we had to restrict ourselves to some representative examples and no claim of completeness is made. As for the liquids, it was limited to those that so far have found more use in the field (i.e., argon, krypton and xenon), although liquid helium and neon have also been proposed for detectors [11,12]. Concerning the applications, the emphasis has been put, somewhat arbitrarily, on the development of detectors for the observation of rare events under low background conditions and for medical imaging. However, electromagnetic calorimeters and time projection chambers (TPCs) are also briefly mentioned, as they probably constitute the most established detection technologies.

This review paper is organised as follows. In Section 2, we present a short compilation and a few comments on the properties of liquid rare gases in view of their use as detector media. In Section 3, electromagnetic calorimeters and time projection chambers are briefly described and representative examples of each of them, as well as of their applications, are presented to illustrate the progress and accomplishments achieved. The reader is referred to the literature for a more complete coverage of the subject. Section 4 is devoted to the challenging development of

LRGD for the search of rare processes in low background experiments with special emphasis on the direct detection of dark matter. Finally, developments of LRGD for medical imaging are described in Section 5.

2 LIQUID RARE GASES AS DETECTOR MEDIA

Some of the most relevant properties of liquid argon, krypton and xenon in view of their use as radiation detector media are summarised in Table 1. For a more complete compilation, as well as a discussion of the spread of the data existing in the literature, the reader is referred to the review papers [3, 4, 13 and references therein].

When a charged particle interacts with a liquefied rare gas it gives rise to electron-ion pairs and excited species. Under an applied electric field, a fraction of those pairs escapes recombination and the electrons drift with velocities of the order of a few mm/ μ s while the ions remain almost stationary during the drift time of electrons, since their drift velocities are 3 to 5 orders of magnitude lower than those of electrons. As the diffusion rate of charges is low (see Table 1), by using suitable electrode designs, charge signals induced by the motion of electrons can provide excellent position resolution. In a liquid argon multi-strip ionization chamber, a resolution of 20 μ m, r.m.s., has been measured with minimum ionizing particles in the plane perpendicular to the electron drift direction [14]. In liquid xenon, by measuring the electron drift time, 20 μ m was obtained with α -particles [15] and about 300 μ m with γ -rays of \sim 500 keV along the drift direction (both values r.m.s.) [16–18]. In the case of γ -rays, the resolution was largely limited by the range of photoelectrons. It is worth to stress that the resolution in the transversal plane depends in a great extent on the arrangement of the readout electrodes. Furthermore, the contribution of the electron diffusion to the resolution is expected to be larger in the

transversal plane than along the electric field direction due to the difference between the transversal and longitudinal diffusion coefficients.

As liquid rare gases have high free electron yield and low Fano factor (Table 1), good energy resolution can be obtained in ionization mode [19–25]. The Fano factor, F , is the ratio of the observed variance of the number of ionizations to that predicted by the Poisson statistics. As one can see from Table 1, F is much smaller than 1 in liquid rare gases. The resolution improves with increasing electric field due to the higher probability for electrons to escape recombination. That improvement is very remarkable up to fields of the order of a few kV/cm, becoming less pronounced at higher fields.

In liquid xenon, the energy resolution for gamma-rays has been measured by several authors for different energies and applied electric fields. Some of those results are compiled in [24] showing good agreement with a $E^{-1/2}$ dependence on the γ -ray energy. Being scaled to 662 keV, most of the results are within the interval from 6.5% to 7.5% (FWHM) [19–21,24,25]. FWHM refers to Full Width at Half Maximum of the distribution.

In liquid argon, a slightly worse energy resolution has been obtained with γ -rays [21]. For 976 keV conversion electrons, a resolution of about 3.5% (FWHM) has been reported [22,23].

In addition, liquefied rare gases are very good scintillators emitting in the ultraviolet. As scintillator, the best LRG is liquid xenon (LXe), as it emits at longer wavelengths, is the fastest and has the highest light yield (very similar to that of NaI(Tl), one of the best known scintillators). On the other hand, the scintillation characteristics of liquid argon (LAr) and liquid krypton (LKr) can be improved by, for instance, doping with a few % of xenon [26–28]. Hence, in LRGD, light can provide a very fast signal for coincidences, trigger for the data acquisition

Table 1. Some properties of liquid argon, krypton and xenon. For more details on the properties of LRG, the reader is referred to the review papers [3,13], as well as [4], and references therein.

		<i>LAr</i>	<i>LKr</i>	<i>LXe</i>
Physical properties	Atomic number	18	36	54
	Boiling point at 1 bar, T_b (K)	87.3	119.8	165.0
	Density at T_b (g/cm^3)	1.40	2.41	2.94
Ionisation	W (eV) ¹	23.6	20.5	15.6
	Fano factor	0.11	\sim 0.06	0.041
	Drift velocity (cm/ μ s) at 3 kV/cm	0.30	0.33	0.26
	Transversal diffusion coefficient at 1 kV/cm (cm^2/s)	\sim 20		\sim 80
Scintillation	Decay time ² , fast (ns)	5	2.1	2.2
	slow (ns)	1000	80	27/45
	Emission peak (nm)	127	150	175
	Light yield ² (phot./Mev)	40000	25000	42000
	Radiation length (cm)	14	4.7	2.8
	Moliere radius (cm)	10.0	6.6	5.7

⁽¹⁾ W is the mean energy required to create a electron-ion pair.

⁽²⁾ For 1 MeV electrons and in the absence of electric field.

system or any other purpose requiring a fast signal promptly related to the particle interaction in the detector. In liquid xenon, time resolutions of ~ 400 ps, r.m.s., have been obtained for gamma-rays of 511 keV [29–31]. Under optimal conditions of light collection the time resolution tends to vary as $E^{-1/2}$. Hence, very good resolution is expected for high energy particles (approximately 30 ps was reported for 2.7 GeV ^{20}Ne ions [32]). Concerning the use of scintillation for spectrometric purposes, the principal difficulty is to provide high and uniform ultraviolet light collection, which is mostly due to the low reflectivity of most materials at these wavelengths. Hence, the energy resolution, as well as the minimum energy detectable and the uniformity, are strongly dependent on the design and materials of the detector. It is difficult to give a representative number for the energy resolution of a scintillation spectrometer. Therefore, we refer to a dedicated review on this subject [13] and only add some recent results as examples: about 17%, FWHM, for 662 keV γ -rays [33,34], 26%, FWHM, for 122 keV γ -rays [35] and 10%, FWHM, for 5 MeV α -particles [30].

Compared to the gas phase, the liquid has the additional obvious advantage of providing larger uniform sensitive masses. This fact, together with the characteristics mentioned above, makes liquid rare gases particularly suitable for building large detectors with tracking and calorimetric capabilities for a wide range of applications.

Taking into account the properties listed in Table 1, liquid xenon is, in principle, the most attractive LRG detector medium for almost all applications: it has the highest Z and density (which implies the highest detection efficiency for gamma-rays and the smallest track length for charged particles), it is the best scintillator and presents a very good set of properties concerning ionization and charge transport. Liquid argon, on the other hand, besides having very small diffusion coefficient, has much lower price and is easier to purify and maintain at the necessary purity during long periods of time, which is attributed mostly to the much lower operating temperature of LAr detectors compared with those employing LXe. This fact also imposes rather severe restrictions on the materials that can be used in contact with LXe which are not so severe in the case of LAr and LKr. Krypton occupies an intermediate position in almost all aspects.

Concerning applications, LXe is so far the only LRG used for medical imaging detectors, where the detection of gamma-rays of a few hundreds keV with high efficiency is at a premium. It is also the best choice, apart from the price, for low energy, low background experiments, where radiopurity is of prime importance. In fact, xenon is free of long living isotopes whereas natural argon has ^{39}Ar and ^{42}Ar β -emitting radioisotopes with half lives of 269 and 33 years, respectively. Although the concentration of these isotopes in natural argon is of the order of 10^{-21}g/g [36,37], it can become a disturbing source of background

for experiments searching for very rare events, especially if these events involve a small deposition of energy in the detector medium, as it is the case of the direct detection of dark matter. Krypton is practically ruled out for low background experiments: ^{85}Kr is a β -emitter with a half-life of 10.8 years, the endpoint of β spectrum is 0.69 MeV and the concentration ratio $^{85}\text{Kr}/\text{Kr}$ is $\sim 10^{-11}$ [38].

In high energy physics (with and without accelerators), in applications requiring very large detector mass, as for calorimetry and/or tracking of high energy particles, liquid argon is the most frequent choice, mostly due to its much lower price and ease in achieving and maintaining purity. Krypton, which is between argon and xenon in these two aspects, is also used in calorimetry, but not so widely as argon. In spite of the price, there are projects of building liquid xenon calorimeters ([13] and references therein), especially for applications where high efficiency detection of medium energy (tens of MeV) γ -rays is of prime importance.

3 ESTABLISHED TECHNOLOGIES AND THEIR APPLICATIONS

3.1 ELECTROMAGNETIC CALORIMETERS

The interaction of high energy (typically > 1 GeV) photons and electrons with matter is dominated by the creation of electron-positron pairs and bremsstrahlung leading to the formation of a cascade of secondary electrons, positrons and photons, which is usually referred as an electromagnetic shower. An electromagnetic calorimeter measures the energy of a high energy photon or electron by containing the shower within the device and providing a signal proportional to the energy of the incoming particle.

Electromagnetic calorimeters for high energy experiments are so far the most well established technology and the most widely spread application of LRG. A common calorimeter configuration is the transverse sampling type where LAr or LKr ionization chambers are interleaved by uranium, iron or lead absorbing plates placed perpendicularly to the incident particle direction (an electron or gamma-ray typically in the GeV range) [39]. The dimensions are such that the detector fully contains the electromagnetic shower and the energy of the incident particle is determined from the energy deposited in the liquid layers. This type of device has found wide application in experiments of high-energy physics [39–42]. The disadvantage of this type of calorimeter lies in the long collection time for the charge (~ 1 μs). To overcome this drawback and cope with the high rates in some of new generation accelerator experiments (with colliders or fixed target), innovative calorimeter concepts, different electrode geometries and ionization readout methods have been developed and implemented. A discussion of these technical aspects is outside the scope of the present paper and can be found

in the literature (for instance, [39,43] and references therein). Examples of new developments are the LAr sampling calorimeter with zigzag longitudinal electrode structure for the ATLAS experiment at CERN [44], the LKr quasi-homogeneous calorimeter with longitudinal electrode structure for the NA48 experiment at CERN [45] and the LKr, as well as LXe, quasi-homogeneous calorimeters with transverse electrodes for the KEDR and CMD-2M experiments in Russia [46]. The construction of large detectors based on these developments are in progress.

Apart from those with ionization readout, calorimeters based on the scintillation of liquid xenon or LXe/LKr have also been proposed ([13] and references therein). Although several prototypes have been constructed and tested, this type of device has not, so far, been used in a real experiment. Among recent developments is a liquid xenon homogenous calorimeter proposed as the γ detector for the experiment MUEGAMMA which searches for the decay of a positive muon into a positron and a gamma-ray, which is forbidden in the standard model [47]. In this experiment, the signature of the process is the back-to-back simultaneous emission of a positron and a 52.8 MeV gamma-ray. To discriminate from the competing processes and other sources of background, a detector with good energy (better than 2%, FWHM), position (a few mm) and time resolutions (≈ 50 ps) for 52.8 MeV gamma-rays is needed. To meet these requirements, a liquid xenon homogenous scintillation detector with an active volume of 800 litres surrounded by 800 photomultipliers (PMTs) was proposed. The position of the gamma-ray interaction is determined from the amplitude distribution of the PMT signals and the energy is obtained from their sum. A 2 litre prototype with 32 PMTs has been tested using radioactive γ -sources. Position and energy resolution of ≈ 3 mm and 4% (both corresponding to one stan-

dard deviation) have been achieved for γ -rays of 1.8 MeV [34]. A 70 litre prototype equipped with 228 PMTs immersed in the liquid has also been constructed and is being tested under 40 MeV γ -ray irradiation [47].

Another proposal for using a scintillation calorimeter based on liquid xenon (or liquid argon doped with Xe) was made for the detection of gamma cascades produced in radiative neutron capture processes in the framework of the n-TOF experiments [48] that aims at measuring the cross section of neutron induced processes. In this case, the main requirements of the detector are very high detection efficiency, in 4π , for γ -rays of energy up to ≈ 10 MeV, good energy resolution and insensitivity to neutrons. The feasibility and design studies have been done [49] and a first prototype is under construction.

3.2 TIME PROJECTION CHAMBERS (TPC)

The Time Projection Chamber (TPC), based on liquid argon or liquid xenon, is another type of liquid rare gas detector that has been proven to work reliably and is being increasingly proposed and used for a variety of particle physics experiments.

The general principle of operation of the device is as follows. A charged particle produces along its path in the liquid free electrons, which drift under an applied electric field towards a system of segmented electrodes. Approaching them, the electrons induce electric signals on the nearest readout elements (e.g., wires, strips, pads). As the electrons from different parts of the track arrive to the readout system at different times, the image of the track is being "projected" in time onto the readout plane. Thus, a set of 2D images of the electron distribution in the chamber volume is obtained allowing a full 3D picture of the event to be reconstructed.

Liquid TPC constitutes a kind of a new generation of bubble chamber, with the advantages of being electronically read-out, operated over a very large continuously sensitive volume, self-triggering (if primary scintillation is also detected), able to provide three-dimensional images of ionising events with simultaneous identification of the particles from their linear energy loss, dE/dx , and range measurements. Furthermore, this type of detector acts also as a homogenous calorimeter with very fine granularity. An inherent characteristic of TPCs is the low counting rate capability due to the long distances (sometimes ~ 1 m) that the electrons have to drift before reaching the readout system.

Liquid argon TPC was proposed by Rubia for studying solar neutrinos and the proton decay [50]. Some details of this device developed in the framework of the ICARUS project will be given in Section 5.2 and further information can be found in the literature [50–53]. Figure 1 shows an example of an event recorded by ICARUS liquid argon

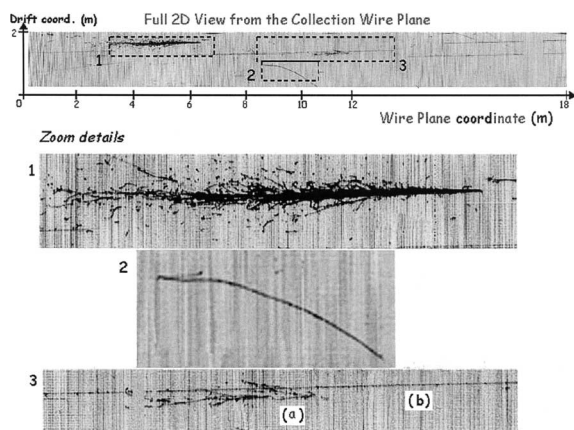


Figure 1. Example of events recorded by ICARUS liquid argon TPC, showing the excellent reconstruction of tracks of high energy particles. 1, an electromagnetic shower; 2, a muon that stops and decays in one electron; 3, electromagnetic shower (a), and part of a 14 meter long muon track (b).

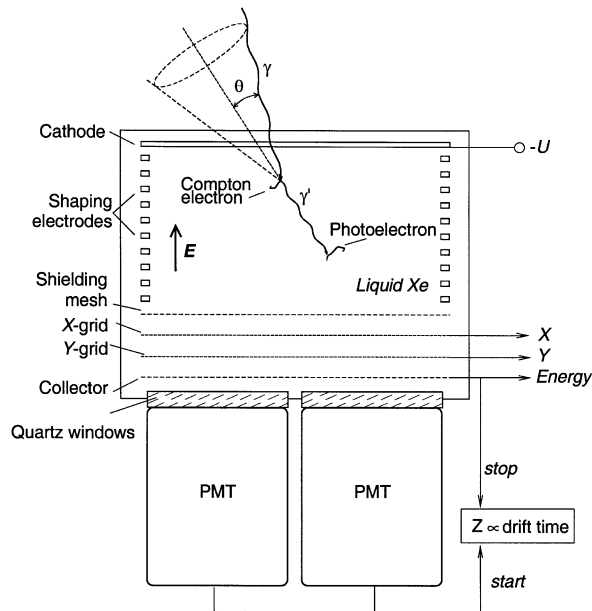


Figure 2. Liquid xenon TPC for γ -ray imaging as a Compton telescope [54]. An incident γ -ray is inelastically scattered in liquid xenon, giving rise to an electron (referred as Compton electron) and a scattered gamma-ray (γ'), followed by the absorption of the scattered photon with the emission of a photoelectron. By measuring the energy deposit and the coordinates (x, y, z) of the two gamma-ray interactions, the energy of the incident γ -ray and the angle θ can be determined. (See Section 3.2 for more details on the principle of operation of this detector.)

TPC demonstrating the excellent capability of this type of device for recording the tracks of high energy particles over long distances.

Liquid xenon TPC is especially suitable for demanding experiments requiring high detection efficiency for gamma-rays in the energy range from hundreds of keV to tens of MeV combined with fast self-trigger, calorimetric and imaging capabilities.

LXe TPC has been developed and successfully used for gamma-ray imaging as a Compton telescope in the energy range from about 0.2 to 20 MeV [54]. This device is referred in the literature as LXeGRIT (Liquid Xenon Gamma-Ray Imaging Telescope) and its principle of operation is schematically depicted in Figure 2. The energy of an incident gamma-ray and its direction of incidence, limited to a conical surface of opening 2θ , are obtained by determining the energy deposits and the three coordinates of the individual γ -ray interactions in the detector sensitive volume (Figure 2). The scintillation light produced in the liquid is detected by four photomultipliers thus providing a prompt trigger. Under the applied electric field E , the electrons due to ionization along the Compton electron and the photoelectron tracks drift towards the wire planes X and Y being collected at the collector electrode. The charge signals induced in the wire planes X and Y are used for determining the x and y

coordinates of the two gamma-ray interactions, while the z coordinate is obtained by the drift time of the electrons using the light as start signal. A detector with an active area of 400 cm^2 and a drift gap of 7 cm has already been tested both on ground and in balloon flights. With a position resolution of $\approx 1 \text{ mm}$ (r.m.s.) along all three directions and an energy resolution (FWHM) $\approx 8.8\%/\sqrt{E}$ (E in MeV), it provides Compton imaging of 1.8 MeV γ -rays with an angular resolution of about 3 degrees (r.m.s.) [55]. A program for the upgrading of LXeGRIT to enhance its energy sensitivity and efficiency of triggering is envisaged [56].

Liquid Xenon TPCs have also been developed and successfully applied in particle physics experiments. An example is the 60-litre LXe TPC that has been used for studying the decay of a pion into a muon, a neutrino and a gamma-ray (i.e., $\pi \rightarrow \mu\nu\gamma$) [10,57]. In this experiment, low threshold for gamma-rays and fast trigger are the main requirements for the detector. A minimum measurable energy of 230 keV was achieved.

A LXe segmented ionization chamber triggered by scintillation, which was proposed for Positron Emission Tomography (PET), can also be considered, to some extent, a high counting rate TPC. We shall describe it in Section 5.

4 LRGD FOR THE SEARCH OF RARE PROCESSES

The new generation of underground experiments without accelerator for studying nuclear and high energy rare processes, i.e., processes whose expected probability of occurrence is very low, pose new and specific challenges, for which novel technologies and detecting methods are required. In these experiments, the remotely probable signal that constitutes the experimental signature of the phenomenon under study has to be disentangled from the background. Consequently, there are two key issues to be considered: i) lowering the background as much as possible by going deep underground, shielding and using ultra-low background materials; ii) using detection methods capable of revealing the signal as much unambiguously as possible, discriminating the residual background (active discrimination).

Liquid rare gas detectors are being increasingly used for rare event experiments, such as those for direct dark matter search, study of neutrinoless double beta decay ($2\beta 0\nu$), proton decay, and some aspects of neutrino physics. In fact, LXe and LAr present very attractive characteristics for these experiments: i) facility in obtaining very large continuously sensitive fiducial volumes of very pure material with very low intrinsic background; ii) high density allowing to obtain a large mass of the detector medium; iii) flexibility for implementing active background discrimination methods; iv) in most cases, the liquid medium can

combine detector and source functions thus increasing the sensitivity of the experiment.

The use of LRGD for the direct detection of dark matter will be considered in some detail, but, due to the limitation of space, the applications of LRGD to other rare events experiments are mentioned only briefly.

4.1 DARK MATTER DIRECT DETECTION

The nature of the dark matter, which makes $\approx 90\%$ of the mass of the Universe, is one of the current issues in astrophysics. WIMPs (Weakly Interacting Massive Particles) are possible dark matter candidates. The most direct method of detecting such a particle is to look to the nuclear recoil resulting from the elastic scattering of the WIMP with a target/detector nucleus. However, the probability of the process is very small and the recoil signals are very weak. Therefore, the mass of the detector ought to be large, the energy threshold should be as low as possible and very good rejection of the background events is indispensable. Furthermore, it is of crucial importance to achieve an extremely high radiopurity of all the components and the sensitive medium of the detector. This set of requirements with an emphasis on an energy threshold as low as possible and high background rejection efficiency, called for new detection techniques and innovative detector designs.

Liquid xenon has appropriate properties: i) it has 48% isotopic content with non-zero nuclear spin, thus being sensitive to both spin-dependent and spin-independent interactions; ii) it has a large atomic mass ($A = 131$) suitable for searching WIMPs with masses between 50 and 500 GeV/c^2 (c is the speed of light in vacuum); iii) it is free of long living radioactive isotopes, except for possible contamination with ^{85}Kr but that can be removed [58]; iv) it has high light and charge yields, therefore allowing a low energy threshold; v) large mass detector is feasible at a reasonable price; vi) its properties allow the implementation of a variety of techniques for discrimination between the signals due to recoil nucleus and those due to background electrons and gamma rays.

Liquid xenon offers several signal/background discrimination methods based on two facts: 1) the electron-ion recombination along the particle track depends significantly on the dE/dx of the particle; 2) a large fraction of the scintillation photons comes from de-excitation of excimers formed in the sequence of the recombination process. One method is based on pulse shape discrimination: in the absence of electric field, the nuclear recoil events produce light signals, which are shorter than those from the electron background events [59]. Another discriminating method takes advantage of the fact that, under an applied electric field, the fraction of electrons escaping recombination is much larger for an electron track than for a densely ionized nuclear recoil trace. For the energies of

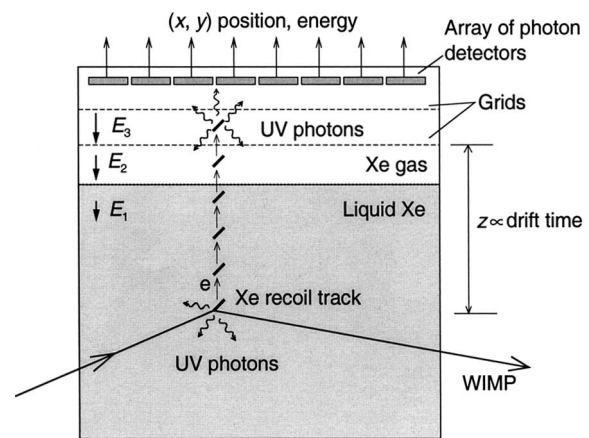


Figure 3. A two-phase detector for WIMP detection [63]. The Xe nuclear recoil resulting from the elastic scattering of a WIMP produces scintillation (referred to as primary) and ionization in the liquid. The electrons drift under the electric field E_1 , are extracted into the gas phase by the field E_2 and are transported into a region where there is a field E_3 high enough for producing secondary scintillation.

interest (~ 1 to ~ 100 keV), the ionization signal is very small and charge multiplication, although occurring in liquid xenon [60,61], requires very high electric fields. One way of overcoming these difficulties is to use a two-phase detector [62,63] (Figure 3): under an applied electric field the electrons drift to the phase boundary and are extracted into the gas phase where they can easily produce secondary scintillation (electroluminescence) or be multiplied. In the case of using secondary scintillation, there are two light signals for each event: the primary and the secondary scintillation signals separated in time by the drift time of electrons. Measurements showed that the ratio of amplitudes of the secondary to the primary signals is much larger for electrons than for recoils [33,64,65]. This allows to discriminate nuclear recoils from γ -rays (Figure 4). Other discrimination schemes potentially available in liquid xenon detectors can be found in references [66–68].

In fact, very low background liquid xenon detectors have been already taking data underground, searching for WIMPs, and others are being developed for future installation. In the framework of the DAMA Collaboration, a liquid xenon scintillation detector has been providing data in the Gran Sasso National Laboratory for already several years [69]. It has ≈ 6.5 kg (i.e., ≈ 2.2 litres) of LXe, Kr-free (to lower the intrinsic radioactivity due to the residual contamination with ^{85}Kr), enriched at 99.5% in ^{129}Xe in order to increase the sensitivity to possible spin-dependent interacting WIMPs. The background rejection is made by pulse shape discrimination. For more details, the reader is referred to the literature [58,69,70]. Another example of a liquid xenon detector entirely based on scintillation readout is ZEPLIN-I, which is taking data since 2001 at Boulby Mine [35]. It is a single phase detector and the fiducial volume with 4 kg of liquid is seen by 3 photo-

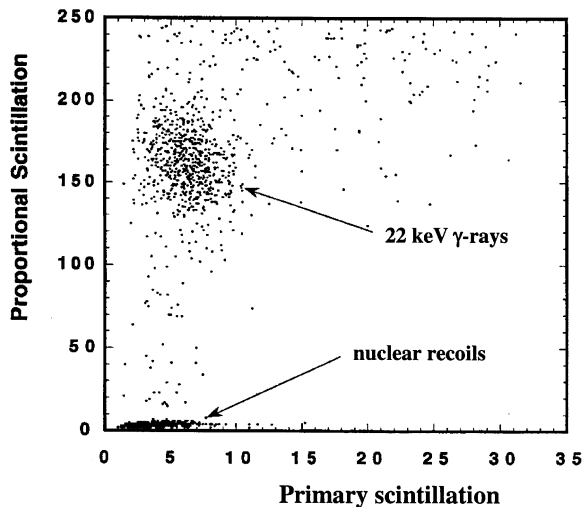


Figure 4. Secondary scintillation (here referred to as proportional scintillation) in the gas vs. primary scintillation in the liquid in a two-phase xenon detector with a mixed gamma-ray and neutron source [33]. Arbitrary units are used in both axis.

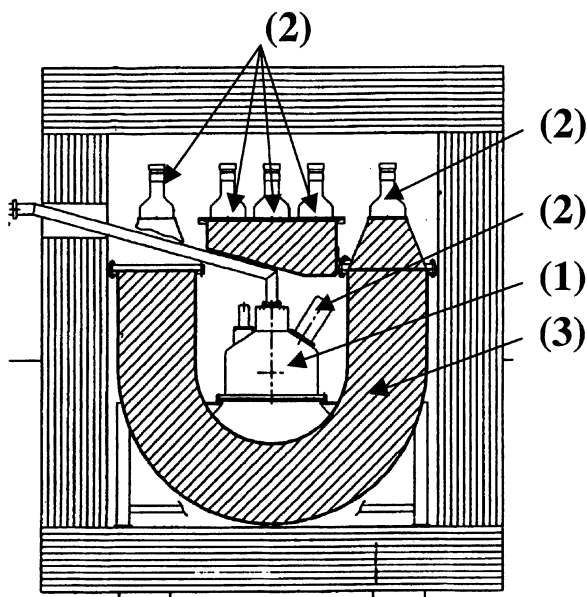


Figure 5. Schematic drawing of the liquid xenon detector ZEPLIN-I [71]. 1, liquid xenon chamber; 2, photomultipliers; 3, liquid organic scintillator for Compton veto shielding.

multipliers (see Figure 5). No electric field is applied, and pulse shape analysis is used for background discrimination.

Among the two-phase xenon detectors proposed for WIMPs search, two are being manufactured at the time of writing (ZEPLIN II and ZEPLIN III) and will also be installed in Boulby Mine. ZEPLIN-II has 35 kg liquid xenon target seen by 7 photomultipliers placed in the gas phase. Electrons extracted from the liquid into the vapour produce secondary scintillation when approaching a plane of wires where a high field region exists. The ratio between

primary and secondary scintillation signal amplitudes is expected to provide a good discrimination of the nuclear recoils against the electron background [65,72–74]. ZEPLIN-III is a kind of “upside-down” version of ZEPLIN-II with smaller gap and lower mass but with a design that improves the light collection and allows operation at higher electric field in order to lower the detector energy threshold which is expected to be of the order of 1 keV: it has a thin slab geometry (3.5 cm drift layer and 0.5 cm electroluminescence gap) with 31 photomultipliers immersed in the liquid. It uses a much higher electric field (up to 20 kV/cm), which is expected to enable the detection of the small ionization signal from the nuclear recoils, thus improving the background discrimination power. The possibility of obtaining position information for further reduction of the background is also investigated [66,75].

The array of ZEPLIN detectors intends to be a test bed for scale-up to a 1-ton liquid xenon detector, which is a part of the WIMP dark matter search programme of the UKDMC at Boulby Mine [66,76].

Recently, two other large double phase xenon detectors for direct WIMPs search have been proposed and are being developed [33,68,77].

4.2 NEUTRINO EXPERIMENTS

Liquid argon [50] and more recently liquid xenon [78] have been proposed as detectors to study the problem of neutrino oscillations, namely, to determine oscillation parameters and neutrino masses.

The ICARUS liquid argon TPC, described in Section 3.2, can be used in multi-purpose experiments and is particularly suited to perform neutrino studies with long baseline beam, atmospheric, supernovae and high energy solar neutrinos [79]. After small scale tests started in 1989 to verify the feasibility of such detector, a 3 ton prototype was constructed and submitted to a Research and Development program which was completed in 1993 [51,52]. The following years have been spent in the development of techniques suitable for the industrial production of large scale detectors. A first 600 ton module, an intermediate step towards the multi-kiloton detector, is already constructed and has successfully undergone above-ground tests [53].

In view of the success of the ICARUS programme, a 70 kton liquid argon TPC (in a second phase expected to 100–200 k ton), named LANNDD (Liquid Argon Neutrino and Nucleon Decay Detector), has been proposed for studying neutrino oscillations and search for the proton decay, aiming at overcoming the sensitivity of other similar experiments [80].

The XMASS collaboration [78] proposed a 10 tons (fiducial mass) liquid xenon detector to measure the low energy $p-p$ and the ${}^7\text{Be}$ solar neutrino spectra. The neutrino detection would rely on the occurrence of νe elastic

scattering in liquid xenon, the recoil electron resulting from the neutrino scattering being the signature of the event. The detector is basically a 4π spectrometer based on liquid xenon scintillation. Pulse shape analysis is intended to be implemented for background discrimination.

4.3 DOUBLE BETA DECAY

Various types of detectors and different emitters are being used to investigate the neutrinoless double beta decay in direct counting experiments [81]. Common goals are to produce the lowest possible background level of the experimental devices, to get the best energy resolution and to obtain redundant information.

An experiment has been running for several years using a multisectional liquid argon ionization chamber where ^{100}Mo is the source of the rare neutrinoless double beta events [37]. The liquid xenon setup of DAMA experiment has also been proved to be useful in searching for neutrinoless double beta decay in ^{134}Xe and ^{136}Xe [82].

5 LRGD FOR MEDICAL IMAGING

Due to its excellent properties as gamma-ray detector medium, liquid xenon is very attractive for nuclear medicine imaging detectors where gamma-rays of energy ranging from 140 keV (typical energy used in scintigraphy and Single Photon Emission Tomography, SPECT) to 511 keV (in the case of Positron Emission Tomography, PET) have to be detected with the highest possible efficiency in order to reduce the dose given to the patient.

As for gamma-cameras for scintigraphy and SPECT, besides high efficiency, good position resolution (< 5 mm) along two directions, as well as good energy resolution (better than 15% at 140 keV) are currently required. The detectors for PET are even more demanding: in addition to the above mentioned requirements, they must have good time resolution (better than a few ns) and high counting rate capability ($A \times \tau_d \leq 4 \mu\text{s.cm}^2$, A and τ_d being the irradiated area and the dead time of a detector module, respectively) [83]. Furthermore, it is desirable to have 3D position information instead of the 2D traditionally provided. This additional feature is fundamental to correct for the parallax error, thus allowing to reduce the size of the ring, and consequently, its geometrical acceptance and price, and to attain the physical limit of the position resolution in the image set by the positron annihilation process itself. It is also necessary for the so-called 3D PET, in which all the pairs of γ -rays are intended to be used and not only those emitted in a thin slice perpendicular to the ring axis.

First proposals for using liquid xenon for a gamma camera were made some 30 years ago and a liquid xenon multi-wire proportional chamber was tested [84]. However, at the high voltages required to attain charge multiplication in the liquid, the wires could not stand the ten-

sion and broke. To overcome this problem, a two-phase camera was proposed [85], with γ -ray absorption in the liquid followed by the drift of electrons towards the liquid-gas interface and the emission of the electrons into the gas where they were multiplied around wires. In this case, the wires could be much thicker because the electric field required to obtain charge amplification in the gas is much lower than in the liquid. The wires were read individually, which required tens of charge sensitive preamplifiers, very expensive at that time. To overcome this drawback, a similar two-phase liquid xenon camera was developed but using the secondary scintillation produced by the electrons in the gas for obtaining position information [86]. The light was detected by an array of photomultipliers and the localisation was attained by computing the centre of gravity of the distribution of light among the PMTs (i.e., by the so-called Anger method). More details about these attempts to develop a liquid xenon gamma camera can be found in [87].

Recently, a new approach taking advantage of the good position resolution potentially available on the basis of the charge signal in the liquid but avoiding the thin wires required for charge amplification has been used. Hence, the design of the chamber is similar to that of [84] but the plane of wires is replaced by a "mini-strip" plate made of 0.5 mm thick glass with metal strips deposited on both sides [88]. The chamber is operated without charge multiplication. The strips are read individually using very low-noise multichannel integrated electronics, nowadays commercially available at a very low price per channel. Position resolution better than 2 mm was obtained with 122 keV gamma-rays [89]. The full characterisation and development of this device is presently under way.

Another recent application of liquid xenon to medical imaging detectors is a liquid xenon multiwire drift chamber with scintillation trigger, developed as a detector module for a PET scanner (Figure 6) [90,17]. The detector profits from the fast scintillation of xenon to make coincidences and to obtain a trigger for the data acquisition, while ionization charge collection is used for accurate 3D localisation in the way similar to the time projection chamber technique, i.e. with one of the coordinates (x in Figure 6) being determined by measuring the electron drift time. In order to minimise the dead time, the drift distance has to be as short as possible. Therefore, the detector is made of an array of ionization cells with drift gap of 5 mm. Most results were obtained with a multiwire read-out of ionization signals but better performance is expected with the mini-strip plate. For 511 keV γ -rays, coincidence time resolution of 1.3 ns (FWHM), energy resolution of 17% (FWHM), total detection efficiency of about 60% have been obtained with a prototype of a detector module [91,92]. Position resolution of 0.8 mm (FWHM) along the drift direction and the depth-of-interaction (z in Figure 6) with precision of 5 mm were measured. It was

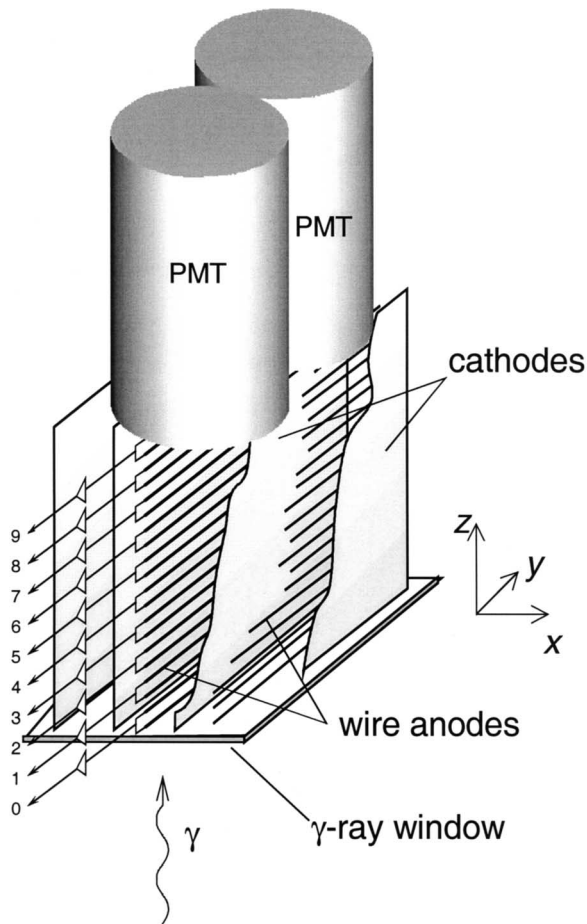


Figure 6. A segment of the liquid xenon ionization chamber for PET. 511 keV γ -rays interact with liquid xenon producing scintillation light and ionization in the liquid. The scintillation is detected by the photomultiplier tubes (PMT) while the charge is collected to a segmented anode (wires, in this version), each segment being read individually (numbered by 0 to 9).

shown that with the mini-strip plate readout, position resolution of ≤ 1 mm in 2D (x and y in Figure 6) and 2 mm for depth-of-interaction (z) can be obtained.

Recently, alternative designs of liquid xenon detector for PET based only on scintillation of the liquid were proposed [31,93]. The scintillation is detected with position sensitive photomultipliers allowing reconstruction of the interaction position. In [31], the light collection is significantly improved by surrounding the sensitive volume with photomultipliers, which form a parallelepiped open at one surface, thus minimising the loss of photons on the reflecting surfaces.

6 CONCLUSION

THE field of liquid rare gas detectors (LRGD) is far from being fully exploited, as demonstrated by the innovative concepts and new applications that are emerging.

Electromagnetic calorimetry based on LRG continues to make progress that will lead to the construction of de-

vices meeting the requirements of the new generation of high-luminosity high energy particle experiments.

The feasibility of large LAr and LXe time projection chambers has been demonstrated and these extremely powerful devices have found increasing application in different research fields.

Some underground experiments for studying rare processes, such as WIMP direct detection, neutrinoless double beta decay ($2\beta 0\nu$), and some aspects of neutrino physics, is presently one of the most challenging and active fields for the application of LRGD.

Finally, liquid xenon detectors for medical imaging are being developed with very promising results.

ACKNOWLEDGMENT

This work was done in the framework of the FCT project CERN/FIS/43729/2001.

REFERENCES

- [1] J.H. Marshall, "On liquid argon ionization chambers of centimetre size", *Rev. Sci. Instrum.*, Vol. 25, pp. 232–237, 1954.
- [2] W.J. Willis and V. Radeka, "Liquid argon ionization chambers as total-absorption detectors", *Nucl. Instr. Meth.*, Vol. 120, pp. 221–236, 1974.
- [3] T. Doke, "Fundamental properties of liquid argon, krypton and xenon as radiation detector media", *Portgal. Phys.*, Vol. 12, pp. 9–48, 1981.
- [4] W.F. Schmidt, *Liquid State Electronics of Insulating Liquids*, CRC Press, New York, 1997.
- [5] A. S. Barabash, "Purification and purity control of working media for liquid ionization detectors", *Instr. Exp. Tech.*, Vol. 31, pp. 517–534, 1988.
- [6] A. Bettini et al., "A study of the factors affecting the electron lifetime in ultra-pure liquid argon", *Nucl. Instr. Meth.*, Vol. A 305, pp. 177–186, 1991.
- [7] E. Aprile, R. Mukherjee and M. Suzuki, "Measurement of the lifetime of conduction electrons in liquid xenon", *Nucl. Instr. Meth.*, Vol. A 300, pp. 343–350, 1991.
- [8] M. Ichige, E. Aprile, T. Doke, K. Hasuine, K. Itoh, J. Kikuchi and K. Masuda, "Measurement of the attenuation length of drifting electrons in liquid xenon", *Nucl. Instr. Meth.*, Vol. A 333, pp. 355–363, 1993.
- [9] S.G. Pokachalov et al., "Spark discharge method of liquid rare-gas purification", *Nucl. Instr. Meth.*, Vol. A 327, pp. 159–162, 1993.
- [10] G. Carugno et al., "A large liquid xenon time projection chamber for the study of the radiative pion decay", *Nucl. Instr. Meth.*, Vol. A 376, pp. 149–154, 1996.
- [11] J.S. Adams, A. Fleischmann, Y.H. Huang, Y.H. Kim, R.E. Lanou, H.J. Maris, and G.M. Seidel, "Energy deposition by electrons in superfluid helium and design of a detector for solar neutrinos", *Nucl. Instr. Meth.*, Vol. A 444, pp. 51–54, 2000.
- [12] D.N. McKinsey and J.M. Doyle, "Liquid helium and liquid neon sensitive, low background, scintillation media for the detection of low energy neutrinos", *J. Low Temp. Phys.*, Vol. 118, p. 153, 2000.
- [13] T. Doke and K. Masuda, "Present status of liquid rare gas scintillation detectors and their application to gamma-ray calorimeters", *Nucl. Instr. Meth.*, Vol. A 420, pp. 62–80, 1999.
- [14] S.E. Derenzo, A.R. Kirschbaum, P.H. Eberhard, R.R. Ross and F.T. Solmitz, "Test of a liquid argon chamber with 20 μm rms resolution", *Nucl. Instr. Meth.*, Vol. 122, pp. 319–327, 1974.
- [15] 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 ionization or proportional scintillation”, Nucl. Instr. Meth., Vol. 160, pp. 239–246, 1979.
- [16] K. Masuda, T. Doke and T. Takahashi, “A liquid xenon position sensitive gamma-ray detector for positron annihilation experiments”, Nucl. Instr. Meth., Vol. 188, pp. 629–638, 1981.
- [17] M.I. Lopes, V. Chepel, V. Solovov, R.F. Marques and A. Policarpo, “Positron emission tomography instrumentation: development of a detector based on liquid xenon”, Proc. Calor99, VIII International Conference on Calorimetry in High Energy Physics, Portugal, Ed. G. Barreira et al., World Scientific, pp. 675–680, 2000.
- [18] V. Chepel, M.I. Lopes, V. Solovov, R. Ferreira Marques, A.J.P.L. Policarpo, “Development of liquid xenon detectors for medical imaging”, Proc. International Workshop on Technique and Application of Xenon Detectors, Kashiwa, Japan, 2001, Eds. Y. Suzuki, M. Nakahata, Y. Koshio and S. Moryama, World Scientific Publishing, pp. 28–40, 2002.
- [19] I.M. Obodovski and S.G. Pokachalov, “Mean energy of ion pair production in liquid and solid xenon”, Sov. J. Low Temp. Phys., Vol. 5, pp. 829–836, 1979.
- [20] I.N. Machulin, V.P. Miroshnichenko, B.U. Rodionov, V.Y. Chepel, A.A. Rostovtsev, V.A. Mashinin and E.V. Skachkov, “Feasibility of precision spectrometry of 1-MeV electrons in liquid xenon”, Sov. Tech. Phys. Lett., Vol. 9, pp. 484–486, 1983.
- [21] A.S. Barabash, A.A. Golubev, O.V. Kazachenko, V.M. Lobashev, B.M. Ovchinnikov and B.E. Stern, “A pulsed liquid ionisation chamber filled with Xe, Ar and CH₄”, Nucl. Instr. Meth., Vol. A236, pp. 69–81, 1985.
- [22] E. Shibamura, A. Hitachi, T. Doke, T. Takahashi, S. Kubota and M. Miyajima, “Drift velocities of electrons, saturation characteristics of ionisation and W-values for conversion electrons in liquid argon, argon-gas mixtures and liquid xenon”, Nucl. Instr. Meth., Vol. 131, pp. 249–258, 1975.
- [23] E. Aprile, J. Park, H. Schwartz and W.H. Ku, “Energy resolution studies of liquid argon ionization detectors”, Nucl. Instr. Meth., Vol. A261, pp. 519–526, 1987.
- [24] E. Aprile, R. Mukherjee and M. Suzuki, “Performance of a liquid xenon ionization chamber irradiated with electrons and gamma-rays”, Nucl. Instr. Meth., Vol. A302, pp. 177–185, 1991.
- [25] E. Aprile, A. Bolotnikov, D. Chen, R. Mukherjee and F. Xu, “Detection of gamma-rays with a 3.5 liter liquid xenon ionization chamber triggered by the primary scintillation light”, Nucl. Instr. Meth., Vol. A 480, pp. 636–650, 2002.
- [26] S. Kubota, M. Hishida, S. Himi, M. Suzuki and J. Ruan(Gen), “The suppression of the slow component in xenon-doped liquid argon scintillation”, Nucl. Instr. Meth., Vol. A327, pp. 71–74, 1993.
- [27] E. Conti, G. Carugno and A. Intravaia, “Time behaviour of the scintillation light in mixtures of liquid argon and xenon”, Nucl. Instr. Meth., Vol. A382, pp. 475–478, 1993.
- [28] D.Yu. Akimov, A.I. Bolozdynya, D.L. Churakov, V.A. Lamkov, A.A. Sadovsky, G.A. Safronov and G.N. Smirnov, “The influence of Xe doping on LKr scintillations”, Nucl. Instr. Meth., Vol. A332, pp. 575–576, 1993.
- [29] V. Chepel, M.I. Lopes, R. Ferreira Marques and A.J.P.L. Policarpo, “Performance study of liquid xenon detector for PET”, Nucl. Instr. Meth., Vol. A392, pp. 427–432, 1997.
- [30] V. Solovov, A. Hitachi, V. Chepel, M.I. Lopes, R.F. Marques and A.J.P.L. Policarpo, “Detection of scintillation light of liquid xenon with a LAAPD”, Nucl. Instr. Meth., Vol. A488, pp. 572–578, 2002.
- [31] F. Nishikido, T. Doke, J. Kikuchi, M. Yamamoto, T. Mori and K. Takizawa, “First test of liquid Xe scintillation detector for PET”, IEEE Nucl. Sci. Symp. Med. Imaging Conf., Norfolk, Virginia, USA, 2002.
- [32] T. Kato, T. Doke, J. Kikuchi, F. Nishikido, H. Okada, K. Morimoto and I. Tanihata, “Time and energy responses of liquid xenon scintillation chamber for ²⁰Ne ion beam at 135A MeV”, Jap. J. Appl. Phys., Vol. 40, pp. 3377–3381, 2001.
- [33] S. Suzuki, “XMASS II: Double phase xenon detector for direct WIMP searches”, 4th Int. Workshop on the Identification of Dark Matter, York, England, 2002.
- [34] S. Mihara et al., “Development of a liquid Xe photon detector for $\mu \rightarrow e\gamma$ decay search experiment at PSI”, IEEE Trans. Nucl. Sci., Vol. 49, pp. 588–591, 2002.
- [35] N.J.T. Smith, “Latest results from ZEPLIN I”, 4th Int. Workshop on the Identification of Dark Matter, York, England, 2002.
- [36] P. Cennini et al., “On atmospheric ³⁹Ar and ⁴²Ar abundance”, Nucl. Instr. Meth., Vol. A 356, pp. 526–529, 1995.
- [37] V.D. Ashitlov, A.S. Barabash, S.G. Belogurov, G. Carugno, S.I. Kononov, I.O. Pilugin, G. Puglierin, R.R. Saakyan and I.A. Vanushin, “Search for double beta decay of ¹⁰⁰Mo with liquid argon ionization chamber”, Nucl. Phys. B (Proc. Suppl.), Vol. 70, pp. 233–235, 1999.
- [38] P. Collon et al., “Measurement of ⁸¹Kr in the atmosphere”, Nucl. Instr. Meth., Vol. B 123, pp. 122–127, 1997.
- [39] D. Schinzel, “High resolution electromagnetic calorimetry with noble gases”, Nucl. Instr. Meth. Vol., A 419, pp. 217–229, 1998.
- [40] P. Franzini (for the D0 Calorimeter Group), “Performance of the D0 Uranium-liquid argon calorimeter modules”, Nucl. Instr. Meth., Vol. A 289, pp. 438–445, 1990.
- [41] L. Apanasevich et al. (Fermilab E706 Collaboration), “Calibration and performance of the E706 lead and liquid argon calorimeter”, Nucl. Instr. Meth., Vol. A 417, pp. 50–68, 1998.
- [42] B. Andrieu et al. (H1 Calorimeter Group), “The H1 liquid argon calorimeter”, Nucl. Instr. Meth., Vol. A 336, pp. 460–498, 1993.
- [43] D. Fournier, “Noble liquid electromagnetic calorimeters”, Nucl. Instr. Meth., Vol. A 367, pp. 5–13, 1995.
- [44] S. Jézéquel (for the ATLAS Collaboration), “The electromagnetic calorimeter of ATLAS and its performance”, Nucl. Instr. Meth., Vol. A 409, pp. 589–592, 1998.
- [45] S. Palestini, “The liquid krypton calorimeter for the experiment CERN-NA48”, Nucl. Instr. Meth., Vol. A 367, pp. 263–266, 1995.
- [46] A. Grebenuk, “Liquid noble gas calorimeters for KEDR and CMD-2M detectors”, Nucl. Instr. Meth., Vol. A 453, pp. 199–204, 2000.
- [47] K. Ozone (for the MUEGAMMA Collaboration), “Liquid Xe detector for mu e gamma search”, International Workshop on Technique and Application of Xenon Detectors, Kashiwa, Japan, 2001, Eds. Y. Suzuki, M. Nakahata, Y. Koshio and S. Moryama, World Scientific Publishing, pp. 41–49, 2002.
- [48] C. Rubia et al., “A high resolution spallation driven facility at the CERN-PS to measure neutron cross-sections in the interval from 1 eV to 250 MeV”, CERN/LHC/98-002, CERN, 1998.
- [49] V. Chepel, F. Neves, J. Pinto da Cunha, and M.I. Lopes, “Feasibility study of liquid xenon/argon 4 π gamma-ray detector for neutron capture measurements” (to be published).
- [50] C. Rubia, “The liquid-argon time projection chamber: a new concept for neutrino detector”, CERN-EP/77-08, 1977.
- [51] A. Bettini et al., “The ICARUS liquid argon TPC: a complete imaging device for particle physics”, Nucl. Instr. Meth., Vol. A 315, pp. 223–228, 1992.
- [52] P. Benetti et al., “A three-ton liquid argon time projection chamber”, Nucl. Instr. and Meth., Vol. A 332, pp. 395–412, 1993.
- [53] J. Rico (for the ICARUS Collaboration), “Status of ICARUS”, presented at XXXVII Rencontres de Moriond (Electroweak Interactions and Unified Theories), Les Arcs (France); hep-ex/0205028, 2002.
- [54] E. Aprile, A. Curioni, V. Egorov, K.L. Giboni, U. Oberlack, S. Ventura, T. Doke, K. Takizawa, E.L. Chupp and P.P. Dunphy, “A liquid xenon time projection chamber for γ -ray imaging in astrophysics: present status and future direction”, Nucl. Instr. Meth., Vol. A 461, pp. 256–261, 2001.
- [55] E. Aprile, U. Oberlack, A. Curioni, V. Egorov, K.L. Giboni, S. Ventura, T. Doke, J. Kikuchi, K. Takizawa, E.L. Chupp and P.P. Dunphy, “Preliminary results from the 1999 balloon flight of Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT)”, SPIE, Vol. 4140, pp. 333–343, 2000.
- [56] E. Aprile, A. Curioni, K.L. Giboni, M. Kobayashi, U. Oberlack, E.L. Chupp, P.P. Dunphy, T. Doke, J. Kikuchi and S. Ventura,

- "The LXeGRIT Compton telescope prototype: current status and future prospects", SPIE, Vol. 4851, pp. 140–150, 2002.
- [57] G. Bessi, G. Carugno, S. Cerdonio, E. Conti, A.T. Meneguzzo and D. Zanello, "New measurement of the $\pi \rightarrow \mu\nu\gamma$ decay", Nucl. Phys., Vol. B 513, pp. 555–572, 1998.
- [58] R. Bernabei et al., "The liquid xenon set-up of the DAMA experiment", Nucl. Instr. and Meth., Vol. A 482, pp. 728–743, 2002.
- [59] D. Akimov et al., "Measurements of scintillation efficiency and pulse shape for low energy recoils in liquid xenon", Nucl. Inst. Meth., Vol. A 524, pp. 245–571, 2002.
- [60] S. E. Derenzo, T. S. Mast, H. Zaklad and R. A. Muller, "Electron avalanche in liquid xenon", Phys. Rev., Vol. A 9, pp. 2582–2591, 1974.
- [61] A.J.P.L. Policarpo et al., "Observation of electron multiplication in liquid xenon with a microstrip plate", Nucl. Inst. Meth., Vol. A 365, pp. 568–571, 1995.
- [62] A. Bolozdynya, V. Egorov, B. Rodionov and V. Miroshnichenko, "Emission detectors", IEEE Trans. Nucl. Sci., Vol. 42, pp. 565–569, 1995.
- [63] A. Bolozdynya, "Two-phase emission detectors and their applications", Nucl. Instr. Meth., Vol. A 422, pp. 314–320, 1999.
- [64] S. Suzuki, "Recent liquid xenon detector techniques for XMASS", LowNu Workshop, Kashiwa, Japan, 2001.
- [65] D. Cline, "A WIMP detector with two-phase liquid xenon", Astropart. Phys., Vol. 12, pp. 373–377, 2000.
- [66] R. Lüscher et al., "The potential of liquid xenon for WIMP Search: the ZEPLIN diagnostic array", Nucl. Phys. B (Proc. Suppl.), Vol. 95, pp. 233–236, 2001.
- [67] H. Wang, "Xenon as a detector for dark matter search", Phys. Rep., Vol. 307, pp. 263–267, 1998.
- [68] E. Aprile et al., "XENON: a 1-ton liquid xenon experiment for dark matter", International Workshop on Technique and Application of Xenon Detectors, Kashiwa, Japan, 2001, Eds. Y.Suzuki, M.Nakahata, Y.Koshio and S.Moryama, World Scientific Publishing, pp. 165–178, 2002.
- [69] R. Bernabei, P. Belli, F. Cappella, R. Cerulli, C.J. Dai, A. Incicchitti, F. Montecchia and D. Prosperi, "Results with the DAMA/LXe experiment at LNGS", Nucl. Phys. B (Proc. Suppl.), Vol. 110, pp. 88–91, 2002.
- [70] R. Bernabei, P. Belli, F. Montecchia, A. Incicchitti, D. Prosperi, C.J. Dai, M. Angelone, P. Batistoni and M. Pillon, "New limits on particle dark matter search with a liquid Xenon target-scintillator", Phys. Lett., Vol. B 436, pp. 379–388, 1998.
- [71] T. J. Sumner et al., "Current limits on the cold dark matter interaction cross section obtained by the UK collaboration", Nucl. Phys. B (Proc. Suppl.), Vol. 70, pp. 74–78, 1999.
- [72] P. Benetti et al., "Detection of energy deposition down to the keV region using liquid xenon", Nucl. Instr. Meth., Vol. A 327, pp. 203–206, 1993.
- [73] D. Cline, Y. Seo, F. Sergiampietri and H.Wang, "A Xe detector for WIMP search", IEEE Trans. Nucl. Sci., Vol. 49, pp. 1238–1242, 2002.
- [74] H. Wang, "The ZEPLIN II liquid xenon dark matter detector", 4th Int. Workshop on the Identification of Dark Matter, York, England, 2002.
- [75] J. Dawson, A. Betiick, D.C.R. Davidge, J.R. Gillespie, A.S. Howard, W.G. Jones, M. Joshi, V.N. Lebedenko, T.J. Sumner and J.J. Quenby, "Monte-Carlo studies of ZEPLIN III", Nucl. Phys. B (Proc. Suppl.), Vol. 110, pp. 109–111, 2002.
- [76] T. J. Sumner, "Xenon detector summary", 4th Int. Workshop on the Identification of Dark Matter, York, England, 2002.
- [77] M. Yamashita, "Gas-liquid double phase Xe detector for direct detection dark matter search by XMASS", International Workshop on Technique and Application of Xenon Detectors, Kashiwa, Japan, 2001, Eds. Y.Suzuki, M.Nakahata, Y.Koshio and S.Moryama, World Scientific Publishing, pp. 136–143, 2002.
- [78] Y. Suzuki (for the Xenon Collaboration), "Low Energy Solar Neutrino Detection by using Liquid Xenon", presented at LowNu Workshop, Sudbury, Canada; hep-ph/0008296, 2000.
- [79] C. Rubia, "Long baseline neutrino oscillations and proton decay: the ICARUS project", Nucl. Phys. B (Proc. Suppl.), Vol. 48, pp. 172–182, 1996.
- [80] D.B. Cline, F. Sergiampietri, J.G. Learned, and K.T. McDonald, "LAANND, a massive liquid argon detector for proton decay, supernova and solar neutrino studies, and a neutrino factory detector", Nucl. Instrum. Meth., Vol. A503, pp. 136–140, 2003.
- [81] A. Morales, "Review on double beta decay experiments and comparison with theory", Nucl. Phys. B (Proc. Suppl.), Vol. 77, pp. 335–345, 1999.
- [82] R. Bernabei, P. Belli, F. Capella, R. Cerulli, F. Montecchia, A. Incicchitti, D. Prosperi and C.J. Dai, "Investigation of $\beta\beta$ decay modes in ^{134}Xe and ^{136}Xe ", Phys. Lett., Vol. B 546, pp. 23–28, 2002.
- [83] W.W. Moses, S.E. Derenzo and T.F. Budinger, "PET detector modules based on novel detector technologies", Nucl. Instr. Meth., Vol. A 353, pp. 189–194, 1994.
- [84] H. Zaklad, S.E. Derenzo and R. Muller, "A liquid xenon radioisotope camera", IEEE Trans. Nucl. Sci., Vol. 19, pp. 206–212, 1972.
- [85] H. Zaklad et al., "Liquid xenon multiwire proportional chamber for nuclear medicine application", Proc. of the First World Congress on Nuclear Medicine, Tokyo, pp. 362–367, 1974.
- [86] 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. Meth., Vol. 205, pp. 373–374, 1983.
- [87] V. Chepel, "Liquid xenon detectors for medical imaging", Physica Medica XII, pp. 15–18, 1996.
- [88] V. Solovov, V. Chepel, A. Pereira, M.I. Lopes, R.F. Marques and A. Policarpo, "Two dimensional readout in a liquid xenon ionisation chamber", Nucl. Instr. Meth., Vol. A 477, pp. 184–190, 2002.
- [89] V. Solovov, V. Chepel, M.I. Lopes, F. Neves, R.Ferreira Marques and A. Policarpo, "Liquid xenon γ -camera with ionisation readout", Nucl. Instr. Meth., Vol. A, 478, pp. 435–439, 2002.
- [90] V. Chepel, "New liquid xenon scintillation detector for positron emission tomography", Nucl. Tracks. Rad. Meas., Vol. 21, pp. 47–51, 1993.
- [91] V. Chepel, V. Solovov, J. van der Marel, M.I. Lopes, P. Crespo, L. Janeiro, Dinis Santos, R.F. Marques and A. Policarpo, "The Liquid Xenon Detector for PET: Recent Results", IEEE Trans. Nucl. Sci., Vol. 46, pp. 1038–1044, 1999.
- [92] P. Crespo, J. van der Marel, V. Chepel, M.I. Lopes, L. Janeiro, Dinis Santos, V. Solovov, R.F. Marques and A. Policarpo, "Pulse Processing for the PET Liquid Xenon Multiwire Chamber", IEEE Trans. on Nucl. Sci., Vol. 47, pp. 2119–2126, 2000.
- [93] J. Collot, S. Jan, and E. Tournier, "A liquid xenon PET camera for neuro-science", Frascati Physics Series, Vol. 21, pp. 305–313, 2000.

This paper is based on a presentation given at the IEEE International Conference on Dielectric Liquids, Graz, 7–12 July 2002.



M. Isabel Lopes received the Ph.D. degree in physics from Coimbra University, Portugal, in 1990. Since 1982, she has been with the Department of Physics of Coimbra University, where she is currently an Auxiliary Professor. She is also a Senior Researcher in the Laboratory of Instrumentation and Experimental Particle Physics in Portugal. Her present principal research interests are electronic and scintillation processes in condensed noble gases, radiation detectors, in particular those using liquefied rare gases, and their applications to medical imaging and dark matter search.



Vitaly Yu. Chepel received the Ph.D. degree in experimental physics from Moscow Engineering and Physics Institute, Russia, in 1988. After graduation, he worked as an engineer and, later, as a researcher at the same institution. In 1992, he moved to the Laboratory of Instrumentation and Experimental Particle Physics in Coimbra, Portugal where he worked as an invited researcher. Currently, he is an Auxiliary Professor of the

Department of Physics at the University of Coimbra and, also, a Senior Researcher in the Laboratory of Instrumentation and Experimental Particle Physics. His principal research interests include development of radiation detectors with a condensed noble gas as a medium and their applications to medical imaging and dark matter search as well as study of relevant processes in noble liquids and solids.