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ABSTRACT

We review here some of the most important chemical-physical and operational properties of the liquid xenon as a detector medium.

1.- INTRODUCTION

In the last few years experimental physicists shown an increasing deal of interest on liquid xenon as a sensitive medium to detect ionizing radiations [1,2,3,4]. Although some of its most important properties are well known since 1960, up to now some technical difficulties prevented it from being widely used for detectors.

The aim of this review is to stress the most important operational properties and possible applications of liquid xenon as a detector medium: ionizing radiations are detected in liquid xenon by scintillation and ionization. Here we will mention also several detectors built and tested by some authors to study these properties.

2.- CHEMICAL AND PHYSICAL PROPERTIES

Xenon is obtained as a by-product from liquefaction and separation of air. It is neither toxic, nor corrosive. Its chemical and physical properties in the gas, liquid and solid phases were extensively studied[5-10]. In particular an updated review of its thermodynamic properties can be found in ref. 11. The solid xenon has a fcc lattice and its volume coefficient of expansion varies from about 10^4 deg^{-1} at 10 K to about $7 \cdot 10^4 \text{ deg}^{-1}$ at 120 K [12,13]. At low partial pressure it produces narcosis in man and because of its high lipid solubility, xenon distributes itself unequally in biological tissues [10].

Some of the physical constants characterizing xenon are summarized in Table 1.

TABLE 1-Summary of liquid xenon physical properties [10,11].

Atomic number	54
Atmospheric Xe (9 stable isotopes)	M.W. = 131.30
Concentration in dry air	0.086 p.p.m.
Abundance	2.9×10^{-9} Wt. %
Boiling point	$T_b = 165.05 \text{ K}$
	$P_b = 1 \text{ atm}$
	$\rho_b = 3.06 \text{ g/cm}^3$
Critical point	$T_c = 289.74 \text{ K}$
	$P_c = 57.6 \text{ atm}$
	$\rho_c = 1.1 \text{ g/cm}^3$
Triple point	$T_t = 161.3 \text{ K}$
	$P_t = 0.805 \text{ atm}$
Heat capacity (163-166 K)	$C_s = 10.65 \text{ cal (g-mole K)}^{-1}$
Heat (latent) of fusion at triple point	$L_f = 548.5 \text{ cal g-mole}^{-1}$
LXe Thermal conductivity	$16.8 \text{ (cal/s cm K)} \cdot 10^{-3}$
Vap. enthalpy	99.3 J/g
Gas/liquid vol. ratio	518.9

3.- SCINTILLATION

The atomic structure of the xenon atom is well known since a long time. The low-lying energy levels, based on observed spectra, are tabulated, for instance, in ref. 14, while a listing of wavelenghts, intensities and photoelectric tracings of the spectra of xenon gas can be found in ref. 15.

An extensive study of the optical properties of condensed xenon and of other noble gases was performed in the period 1960 - 1970^[16]. J. Jortner et al.^[17] studied the emission spectra of condensed rare gases under α -particle excitation. As regards xenon they gave $\lambda = 175 \pm 1$ nm with a width $\Delta\lambda = 15 \pm 2$ nm for the gas at 300 K, $\lambda = 178 \pm 1$ nm and $\Delta\lambda = 14 \pm 2$ nm for the liquid at 160 K, $\lambda = 172 \pm 1$ nm and $\Delta\lambda = 15 \pm 2$ nm for the solid at 140 K and $\lambda = 170 \pm 1$ nm and $\Delta\lambda = 15 \pm 2$ nm at 77 K. The only information given about the purity of the xenon used is that the content of nitrogen, hydrogen and of other rare gases was less than 0.01%. In particular nitrogen was certainly less than 10 ppm. The fluorescent spectra of the solid at 4.2 K, excited by 10-30 KeV electrons, was measured by E.E. Huber et al.^[18] that found a single 7 nm wide band centered near 175 nm. The authors declare only the initial level of contaminations in the gas ($N_2 \leq 10$ ppm, $O_2 \leq 1$ ppm, hydrocarbons ≤ 0.5 ppm, $H_2O \leq 1$ ppm).

The quoted wavelenghts for the emission spectra have to be compared with the corresponding ones for the absorption atomic transitions. The values quoted in ref. 19-21 for the absorption doublet (the most intense ones) are 147 nm and 130 nm for the transitions in the gas and 145 nm and 129 nm for those in the solid. In particular for the solid the absorption spectra was measured by O. Schnepf and K. Dressler^[22] at 4.2 K using a source of Kr. They found four absorption bands (151, 149, 136, 131 nm with a relative intensity 1:10:3:10) in the region between 151 and 120 nm, three of which result within less than 2 nm of gas atomic absorption transitions and are shifted to lower energy. However unfortunately, the purity of the gas used is not quoted. A subsequent investigation between 20 and 50 K in the region from 160 to 90 nm confirmed within the measured band widths the presence of the last three bands but not of the first one^[23]. For the doublet the measured values agree with those of O. Schnepf et al. after an annealing procedure.

As regards scintillation, there are some arguments to take an interest in liquid xenon^[24]. The first indications that it may approach NaI(Tl) in light output date back to '58 when J.A. Northrop et al.^[25,26] performed a survey investigation about the relative efficiencies of gas, solid and liquid xenon, krypton and argon. The high atomic number and the high density of liquid xenon make it a very attractive medium to detect photons. In particular liquid xenon has a fast temporal response: the fast decay time is of about 3 ns and gives the 96% of the emitted light, while, anyhow, the slow decay time is of only about 25 ns^[27,28]. Together with the high value of tolerance estimated for radiation damage ($\approx 10^7$ rad), this property may be important e.g. in the monitoring of high intensity photon beams. Considering the typical decay times of the inorganic scintillators actually used (see Table 2), liquid xenon could be very competitive without showing the known drawbacks of these mediums.

TABLE 2-Characteristics of some scintillation media [4,29] .

Scintillation	LXe	NaI(Tl)	BaF ₂	BGO
Fast decay time (ns)	3	230	0.6	60
Slow decay time (ns)	25	–	620	300
Fast/slow ratio	25	–	0.09	0.05
Rel. output from α	0.137	1.0	0.006	0.08
Ratio α/e	1.1±0.2	0.5	0.34	0.23
K_B^{-1} *(MeV/cm)	30600	3670	–	500
Rad. length (cm)	2.8 at b.p.	2.59	2.05	1.12
$(dE/dx)_{min}$ (MeV/cm)	3.9	4.85	6.6	9.0
refractive index	1.41	1.85	1.56	2.15

* The K_B^{-1} in Table 2 is the Birk's constant parametrizing saturation in luminosity.

Liquid xenon should show a linear response on a wide dynamical range, with a scintillation efficiency higher than that of BGO and an energetic resolution comparable with that of NaI(Tl)^[30] Furthermore for "thin" detectors the photofraction, defined as ratio of the number of photopeak events to the number of total events, is greater in liquid xenon compared to sodium iodide and germanium^[31].

The only scintillation spectrometer built till now has a small volume of about 17 cm³^[32]. The scintillation efficiency and the energy resolution, with the typical behaviour $1/\sqrt{E}$, are very similar to that of NaI(Tl) till $E_\gamma \simeq 100$ KeV. At higher energies the energy resolution becomes worse probably due to disuniformities in the light collection. Furthermore the authors do not declare the level of contaminants left in the xenon after the purification procedure so it is not well clear how much this problem can be critical for spectrometric purposes.

The more critical impurities could be all that absorb UV light such as nitrogen, water, hydrocarbons and so on^[16,33–37]. Nitrogen behaves partially as a wave shifter, but not so efficient to be useful in practice, and as a poison degrading the scintillation light response. The first attempts to study the effect of nitrogen on scintillation in rare gases date back to 1950-1960 ^[38].

One of the main problems to overcome studying scintillation in liquid xenon apart from purification, is light collection because it emits in far UV. There are two possibilities: either using a suitable phototube with an UV window (e.g. MgF₂, LiF₂), but in this case a material with a good reflective coefficient for UV is needed for the experimental vessel, or using a common phototube with a glass window and a wave shifter coated on the internal surface (for example a Pyrex glass coated with sodium salicylate). Generally this last solution is the most widely adopted but it can give drawbacks working with high purified xenon. A very interesting investigation about scintillation light collection in the photon spectral region between 105 and 300 nm is represented by a read-out system using liquid or solid photocathodes ^[39]. They consist of metal cathodes covered with liquid or solid organic layers, such as warm liquids, their solutions or their corresponding solids. The

results obtained up to now for the quantum efficiency are very promising and encouraging for a further development.

4.- IONIZATION

Some properties of ionization in liquid xenon are given in Table 3 compared with that of liquid argon and room-temperature liquids.

TABLE 3- Ionization characteristics of some liquid media [4,40,41].

Ionization	LXe	LAr	TMS	TMP
W-value (eV/pair)	15.6±0.3	23.6±0.3	≤ 73	≤ 71
Fano-factor	0.041-0.059	0.107-0.116	-	-
Low field μ_e (cm ² s ⁻¹ V ⁻¹)	2000±200	525	100	45
v_d (10 ⁵ cm s ⁻¹) at 15 kV/cm	3	5	15	4.5
Rel. output of a mip	12.6	4.6	1	1.1
K_B^{-1} (MeV/cm)	300	200	-	70

In the liquid state of rare gases the average energy required to form a ion pair, W , is smaller than the corresponding value in the gaseous state, as predicted by Doke et al.[42] assuming for the liquid the same electronic band structure as in the solid. This difference is more sensible for xenon. There are a lot of W measurements available in literature[43-48] varying in the range from 7.3 eV to 23.4 eV, but the most reliable seems to be that by Takahashi et al.[49] by internal conversion electrons from ²⁰⁷Bi giving $W = (15.6±0.3)$ eV, while in gaseous xenon W is estimated 21.9-21.5 eV[50,51].

Assuming the hypothesis by Doke, the authors give a theoretical value for W of 15.4 eV considering the energetic balance governed by Platzman's equation:

$$\frac{W}{E_g} = \frac{E_i}{E_g} + \frac{E_{ex}}{E_g} \frac{N_{ex}}{N_i} + \frac{\epsilon}{E_g},$$

where N_i is the mean number of ion pairs produced at an average energy expenditure of E_i , N_{ex} the number of excitons at an average energy expenditure of E_{ex} , ϵ the average kinetic energy of subexcitation electrons and E_g the gap energy. An interesting characteristic of liquid xenon is that the ratio of the number of excitons to that of ion pairs is extremely small, $\frac{N_{ex}}{N_{ion}} \simeq 0.06$. It follows that the Fano factor is small too, as shown in Table 3. It is important to stress that the product of the calculated Fano factor and the measured average energy to create a ion pair is $FW \simeq 0.64$ eV/pair, comparable to a value $\simeq 0.61$ eV/pair for germanium[40]. In particular, for a ionization pulse chamber filled with liquid xenon, it was estimated[52] an energy resolution of $FWHM \simeq 3$ KeV for 1 MeV electrons, taking into account of the electronic noise level in the electronic amplification system. On the other side for a conventional Ge(Li) a typical value obtained is $FWHM \simeq 1.5$ KeV for 1 MeV photons. In conclusion liquid xenon seems a very promising medium to detect gamma-rays, in particular for spectrometric purposes.

The experimental results obtained till now for the energetic resolutions with ionization chambers are in good agreement.

In the experiment of T. Takahashi et al. to measure W [⁴⁹], the ionization chamber used had an energetic resolution of 6-7% for the γ of 569 KeV (²⁰⁷Bi) at 17.3 kV/cm. At lower field values the resolution increases reaching about 13% at 1 kV/cm. Analogous results were obtained by I.M. Obodovsky et al.[⁵³]. Using γ of 662 KeV (¹³⁷Cs) they measured an energetic resolution of 6-7% at 9.5 kV/cm. A ionization chamber was used also by M.C. Gadenne et al.[⁴⁸] to measure W . They obtained an energetic resolution of 8% for the γ of 1.33 MeV (⁶⁰Co) at 3 kV/cm. Always using a ionization chamber Th. Lindblad et al.[²⁹] gave a resolution of 8.6% for the γ of 570 KeV and 6% for the γ of 1060 KeV of ²⁰⁷Bi at 8 kV/cm. In the work by E. Shibamura et al.[⁴⁷] there are compared the pulse height spectra for internal conversion electrons emitted by ²⁰⁷Bi in a ionization chamber filled respectively with liquid argon, argon-xenon mixture and xenon. A little percentage of xenon added in argon improves the energetic resolution compared with that of purified liquid argon. The obtained energy resolution is not quoted in the case of xenon but is shown as in the two spectra the peaks of K-conversion electrons (0.976 MeV e 0.48 MeV) are lower than that of L-conversion electrons (1.05 MeV e 0.55 MeV). The situation is inverted respect to argon behaviour probably due to the higher absorption photoelectric coefficient value in liquid in liquid xenon.

Large ionization chambers were used by K. Masuda et al.[⁵⁴] and by A.S. Barabash et al.[⁵⁵].

For the first ones the measured values of the squared energy resolution $(\frac{\Delta R}{R})^2$, after subtracting the electric noise, show a linear trend when they are plotted as a function of the reciprocal of the gamma-ray energy $1/E_\gamma$. Explicity $(\frac{\Delta R}{R})^2 = \frac{51}{E_\gamma}$. The energy resolution $\frac{\Delta R}{R}$ becomes rapidly better up to an electric field strenght between the cathode and the grid $E_{KG} \simeq 2$ kV/cm, while it improves slowly at higher fields with a value of about 8.6% at 6.5 kV/cm for γ collimated of 662KeV (¹³⁷Cs). In addition, the comparison with the response of a NaI(Tl) crystal of $1\frac{3}{4}$ in diameter \times 2in, shows a better energetic resolution for liquid xenon above an energy of about 1600 KeV.

For the second apparatus it was reached an energetic resolution of 4.9% for the γ of 1836 KeV (⁸⁸Y) at $E = 3.2$ kV/cm. This resolution increases to 9% at 0.5 kV/cm.

However theoretical calculations estimate - depending from the used model - energy resolutions even one order of magnitude better than the experimental values.

In liquid xenon the electron avalanche process occurs typically at field of about $1-2 \cdot 10^6$ V/cm. As regards ionization properties, liquid xenon does not behave as a gas of the same density but as a gas with an "effective density" of (0.113 ± 0.011) g/cm³, approximately 27 times smaller. This becomes clear by plotting the ionization coefficient η , defined as ratio of the first Townsend coefficient to the electric field strenght, as a function of E/ρ for the liquid and the gas as in ref 56.

The drift velocity of electrons measured in liquid xenon is not so far from that obtained in the gaseous state. In particular is $\simeq 3 \cdot 10^5$ cm/s for electric field strenghts E greater than 1 kV/cm [^{56,47}] and saturates very rapidly. At this field value the drift velocity in TMP and TMS are only $4 \cdot 10^4$ and 10^5 respectively[⁴¹].

Furthermore liquid xenon exhibits the higher ratio of electric mobilities at low and high values of the electric field strength and the drift velocity of electrons saturates at lower electric fields comparatively to that necessary in liquid argon [57]. This property makes liquid xenon a very promising detector medium for drift chambers.

The spatial resolution achieved in the liquid phase is obviously better for a lower number of fluctuations in primary ionization and because diffusion is less important. In fact the diffusion coefficient D is 1/50 times smaller in the liquid with a value of $50\text{-}80\text{ cm}^2\text{s}^{-1}$. The detectors tested till now found spatial resolution of $\pm 15\text{-}20\text{ }\mu\text{m}$ for α particles using a MWIC and a drift chamber [58,59], and $\pm 0.6\text{ mm}$ for γ -rays da 662 KeV using a single wire drift chamber [60], while a spatial resolution of $\pm 10\text{ }\mu\text{m}$ for minimum ionization particles was estimated. Hence, liquid xenon seems to be a suitable detector medium for position detectors. Due to the fact that the drift time of electrons depends critically by temperature (a linear dependence $t_d(\mu\text{s}) = 0.130 T (\text{K}) + 0.94$ in the experimental conditions of ref. 60) a maximum temperature variation during the measurements to within $\pm 0.2\text{ }^\circ\text{C}$ is recommended by the authors.

5.- PROPORTIONAL SCINTILLATION

Another very important process to be considered is known as "proportional scintillation". It occurs in liquid xenon as well as in the gaseous state where it was investigated in detail [61-65]. In this last case one detects both the ionization pulse and the scintillation one. This scintillation arises by the primary electrons produced by the interaction of the charge particles with the detection medium. These electrons produce light pulses when they are accelerated in an electric field. This process has a threshold: in a first approximation, for a given gas and pressure it exists a minimum value of the electric field strength E_{th} to emit secondary light. Therefore, it is possible to have proportional scintillation if the counter works both in ionization mode with $E_{th} \leq E \leq E_{ion}$ (minimum value of the electric field strength to have charge multiplication) and in proportional mode. In the gas, working in ionization mode, the light gain expressed as a ratio of secondary light output to primary light output, ranges from 5 to 18, depending from the electric field geometry. Anyhow, in proportional scintillation the energetic resolution and the localization of the light source become better. In fact, the relative variance of the charge gas multiplication factor is compensated by a decreasing of the photomultiplier contribution in the relative variance of the light pulses, so that an overall improvement of energetic resolution is obtained [66].

The chance to use the scintillation signal to restore the leaking of collected charge information is very attractive, but in liquid xenon the study of proportional scintillation needs a further investigation [67]. In ref. 59 it is shown a typical example of a drift time measurement for the electrons generated by α particles of a ^{210}Po source in a liquid xenon drift chamber using a time-to-pulse-height converter (TPC). The obtained spatial resolution is better when the chamber works in proportional scintillation mode. In addition the resolution of the proportional scintillation becomes better at increasing anode potential. From the data of ref.59 the energetic resolution (square of the FWHM) against the reciprocal of the pulse height for proportional scintillation signals is $(\text{FWHM}\%)^2 = 0.15 + 0.26 (\text{relative pulse height})^{-1}$. The limiting value of about 15% is due, probably, to the

fluctuations in the number of electrons free from recombination with ions, because only 5% of ion pairs generated by an α particle produce proportional scintillation.

Some properties of proportional scintillation in liquid xenon were studied by Masuda et al. using a proportional scintillation counter [68] and a ^{207}Bi source. The charge gain Q versus the voltage difference V between cathode and anode wire shows a plateau corresponding to the saturation value of the ionization chamber mode. In addition the beginning of the electron avalanche is at a V value varying from $\simeq 1.5$ kV to $\simeq 5$ kV when the diameter of the central wire changes from $4 \mu\text{m}$ to $20 \mu\text{m}$. On the other side, with increasing V , the photon yield of proportional scintillation L increases of a factor 10^2 at V values ranging from 0.5 to 2.3 kV, for a diameter of the central wire of $4 \mu\text{m}$, and increases at a higher rate as the electron avalanche occurs.

An empirical linear relation between proportional scintillation light and electric field strength was found by Conde et al. [69] for a gaseous xenon proportional scintillation counter, under the hypothesis of parallel plate geometry:

$$\frac{1}{p} \frac{dn}{dr} = -a + b \frac{E}{p} (\text{photons/electron}) \text{cm}^{-1} \text{torr}^{-1}$$

with $a = 0.0074$ and $b = 0.0066$, $\frac{dn}{dr}$ is the number of photons produced by an initial electron per cm, E the electric field strength (V/cm) and p the gas pressure. In this way the threshold field strength is $E_{th} = a \frac{p}{b}$. In particular, Masuda et al. [68], assuming such a linear relation true for liquid xenon and cylindrical geometry too, found:

$$L = Br_1 \left[E_{th} + E_s \left(\ln \frac{E_s}{A} - 1 \right) \right]$$

where r_1 is the central wire radius, B a constant proportional to b , $E_s = \frac{V}{r_1 \ln \frac{r_2}{r_1}}$ the electric field strength on the surface of the central wire. The best fit values of E_{th} are typically in the range $4.0\text{-}7.0 \cdot 10^5$.

One of the most crucial problem to solve in developing liquid xenon detectors is that of purification. In the last few years it has been considered a crucial problem studying electron drift time in condensed noble gas and room-temperature liquids [57,70-73]. The obvious effect of impurities is absorbing energy in collisions with excited atoms or for direct photon absorption, decreasing detected energy. The most dangerous impurities to study ionization are the electroaffine ones (O_2 , CO , CO_2 , H_2O). There are some methods commonly adopted to overcome this problem depending from the impurities: a) physical adsorption by fractional distillation, b) chemical adsorption by nickel on Kieselguhr adsorbent (Ni/SiO_2) or other metallic getters, zeolites and activated charcoal, c) current purification for the electronegative impurities. It is also necessary to use very clean materials and, before filling with xenon, degassing the apparatus at high temperature and producing an ultra high vacuum of about 10^{-10} bar. For oxygen the lower level of contaminations was reached by K. Masuda et al. with a concentration of 1.8 ppb [60], which means that the mean free path for the electron attachment is about 1m and by Barabash et al. that achieved a concentration of 0.1 ppb [55]. For liquid xenon partial results for ionization are from Yoshino et al. [74].

It is not available a detailed study about doping liquid xenon with hydrocarbons, some data [74] for butane, with a concentration of $1.9 \cdot 10^{20} \text{ cm}^{-3}$, show an electron drift velocity of $2 \cdot 10^6$ at 100 kV/cm.

Anyhow in this field a lot of efforts must be done to completely understand the problem. Recently, the doping effect with triethylamine (TEA) or trimethylamine (TMA) in liquid xenon was studied using a small multiwire chamber [75]. The results obtained with TEA for ^{210}Po (α particles) and ^{207}Bi (electrons and photons, are the most promising giving an improvement of the energy spectrum. The α -peak moves up above the 1 MeV peak due to ^{207}Bi as a result of photoionization of TEA. In ionization mode, doping liquid xenon with 45 ppm of TEA, the energy resolution is improved from 15% to 4% (FWHM) for α particles, for an applied voltage to the wires $V_w = 2 \text{ kV}$, and from 16% to 11% for the 1 MeV peak due to ^{207}Bi .

If liquid xenon is doped with TEA and TMA the collected charge at $V_w = 1 \text{ kV}$, increases of a factor 10 for ^{210}Po α particles and of a factor $\simeq 1.3$ for 1 MeV peaks due to ^{207}Bi source. Due to ionization of TEA and TMA by photons emitted in proportional scintillation it follows a new multiplication process that produces again proportional scintillation. This effect, not seen for pure liquid xenon, increases the collected charge sharply around $V_w = 3 \text{ kV}$. Anyhow it is possible to control the process choosing thicker wires.

A measure of electron multiplication in liquid xenon doped with TMA was performed by T. Sano et al.[76] with a single wire counter and a ^{207}Bi source. The multiplication factor increases from 23 with 9.3 ppm of TMA to a value of 45 with 118 ppm of TMA.

6.- CONCLUSIONS

Remarkably enough, some promising ideas emerged from liquid xenon properties outlined above. Both its scintillation and ionization properties make it a very suitable detector medium to realize photon-beam monitors and electromagnetics calorimeters as well as ionization, drift, multiwire chambers. However, further big efforts are needed to realize the possibilities of using liquid xenon in large volume detectors.

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