

DEVELOPMENT RESEARCH ON A HIGHLY LUMINOUS CONDENSED XENON SCINTILLATOR

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Received 16 February 1976

The authors have investigated the means of creating a maximal amount of light by absorption of gamma radiation in condensed xenon. One of the methods relies on the light production around wires in liquid xenon when several kilovolts are applied to them. Another method uses the saturating vapour present over solid xenon; the electric field pulls out electrons from the solid and accelerates them in the gas phase so that they produced light by inelastic collisions.

1. Introduction

The gamma ray stopping power of solid xenon is very close to that of sodium iodide. The photoelectric yield and atomic number of xenon and iodide are quite the same. Xenon is a liquid which at atmospheric pressure boils at 165 K and its density is 3 g/cm³. It solidifies at 160 K and its density becomes then 3.6 g/cm³. The electron mobility allows collection of the charge created in liquid or solid xenon. In a highly purified system attachment is avoided for electron travels below 1 cm. In liquid xenon the mean ionization energy is 16.5 eV¹) and the Fano factor measured in the gas amounts to 0.2²). If only these parameters were involved the energy resolution (fwhm) would be 1.2% for 140 keV. This is the energy of Technetium-99m routinely used in nuclear medicine. A group of authors³) have built a multiwire camera with liquid xenon as detector. The diameter of the wires varied between 3.5 and 5 µm, this size being required to work in the proportional region of electronic multiplication. The observed fwhm is never better than 20%. This value is thought by the authors to be due to the insufficient homogeneity of the electrical field on the wires. In order to obtain a better energy resolution, we tried larger diameter wires (20–50 µm). But as electrical microbreaks occur, when raising the voltage before electronic multiplication is obtained, we operate at lower voltages and observe the light due to excited states with a photomultiplier tube (PMT). The second method was inspired by the work of Zaklad³) and Dolgosheim⁴). These two groups have

shown the possibility of extracting electrons from liquid xenon to the gas phase. With a dual-phase solid-gas system, three features are of great interest for its use as a detector:

- it works in any position,
- the light avalanche without electronic multiplication^{2,5,12}) makes it a very luminous scintillator that can be coupled to an image tube,
- the absence of electronic multiplication avoids space charge creation on the solid-gas interface prejudicial to spectrometric measurements.

2. Liquid xenon; material and methods

The detector and its cooled housing are similar to those described by Gadenne¹). The chamber is degassed under vacuum at 110°C for 48 h previously to its filling. The xenon is of the N 25* quality, it contains 0.5% krypton. To simplify the procedure, xenon is purified only by means of an oxysorb† capsule mainly capturing oxygen and water vapour. The original set-up¹) is modified as follows (see fig. 1). The lower part of the detector has a glass window. A lucite light pipe 60 mm long is inserted through a hole in the expanded polystyrene.

The pipe itself is optically coupled to a PMT thus insulated from the cold source. The cathode, cap shaped, bears in its center a 3 mm diameter Americium source. A wire stretched parallel both to the cathode and to the window is connected to a positive high voltage supply. The window is coated with sodium salicylate over a diameter of 15 mm. This layer converts the emitted UV light into a blue radiation which excites the PMT photocathode.

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* Air Liquide firm appellation.

† Messer Griesheim G.m.b.H. trade mark (4 Düsseldorf, Homberger Strasse 12). Principal constituents are silicagel and chromium trioxide.

3. Results

Whenever an α -particle is emitted, the PMT successively sees: the scintillation generated on the cathode, then the light flashes created by electrons escaping recombination and emitting photons in the neighbourhood of the wires due to the intense electrical field. The first scintillation is the reference by which the following one is measured. Measuring the number of charges allows to ascertain the number of photons created by an electron and to estimate the amount of light which would be obtained with the gamma source. Three parameters have been modified in the course of this study: the distance between the wire and the cathode (b), the vapour pressure over the liquid (p) and the wire diameter (d).

Case a. $b = 0.9$ mm; $d = 50$ μ m.

The maximum allowable voltage for 168 K and 130 kPa is 5.5 kV. The field on the wire is evaluated to be 0.5 MV/cm.

Although no electron multiplication exists for such a field⁷⁾, a break occurs between wire and cathode with a higher voltage. Guessing that this phenomenon may be originated by bubbles, we have increased the pressure either by rapid gas overpressure or by temperature modification. For the pressure of 200 kPa either at 168 or 180 K the voltage can be increased to 6.5 kV. The results shown on fig. 2 were obtained at 6 kV. A large dispersion in the arrival time of the second scintillation is seen: 360 ns for the fastest and 900 ns for the slowest ones. This is due to the α -source dimension. If V_c is the voltage and E_c the electric field on the wire for which the second scintillation can just be perceived, the work provided by the field to an electron above E_c can be expressed as follows:

$$\Delta V = \int_x^{+d} -E dx = \frac{V}{\log 4b/d} \log V/V_c;$$

with: $V_c = 4$ kV, $E_c = 0.37$ MV/cm, $V = 6$ kV one finds: $\Delta V = 560$ V.

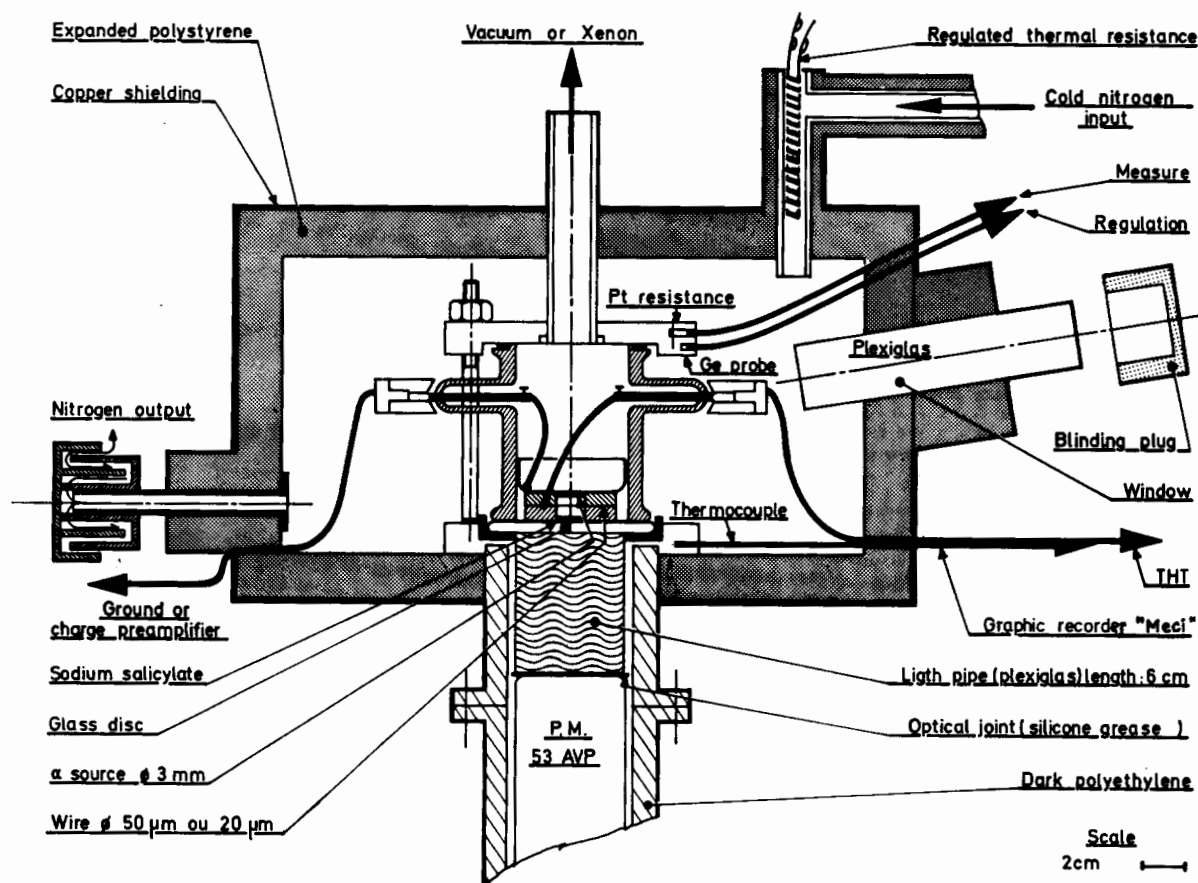


Fig. 1. Liquid xenon assembly.

Case b. $b = 4.1$ mm; $d = 50$ μ m.

At 13 kV the pulses created near the wire are better packed (fig. 3). The time abscissa is multiplied by a factor 2.5 relatively to fig. 2. With $V_c = 10$ kV, $E_c = 0.69$ MV/cm, $V = 13$ kV, ΔV is equal to 580 V. At 189 K (360 kPa), the breaks begin around 18 kV corresponding to a field of 1.25 MV/cm on the wire. Fig. 4 shows that at 17 kV there is a saturation of the

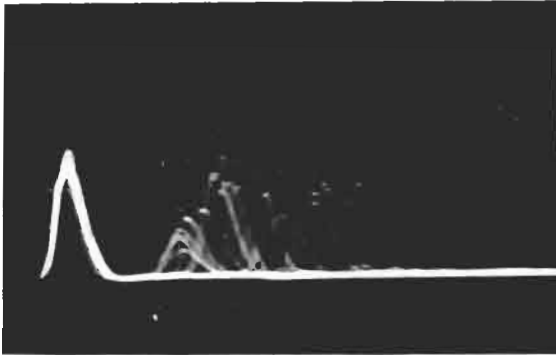


Fig. 2. PM signal. $b = 0.9$ mm; $p = 25$ μ m; $V = 6$ kV. Horizontal sweep: 200 ns/division.

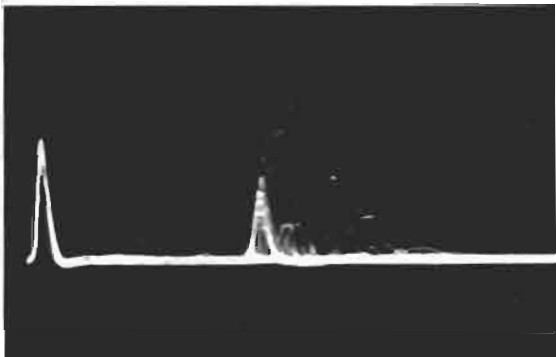


Fig. 3. PM signal. $b = 4.1$ mm; $p = 25$ μ m; $V = 13$ kV. Horizontal sweep: 500 ns/division.

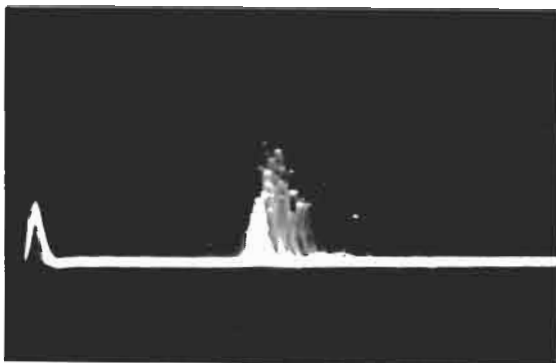


Fig. 4. PM signal. $b = 4.1$ mm; $p = 25$ μ m; $V = 17$ kV. Horizontal sweep: 500 ns/division.

light emitted near the wire. The largest pulses are only twice as big as those of the cathode scintillations instead of 1.6 factor observed at 13 kV.

Case c. $b = 4.1$ mm; $d = 20$ μ m.

With $V_c = 5$ kV, $E_c = 0.75$ MV/cm, $V = 8$ kV, ΔV is equal to 560 V; the breaks begin around 10 kV for $T = 189$ K and $p = 320$ kPa. Pulses have their amplitude better packed (fig. 5).



Fig. 5. PM signal. $b = 4.1$ mm; $p = 10$ μ m; $V = 8$ kV. Horizontal sweep: 500 ns/division.

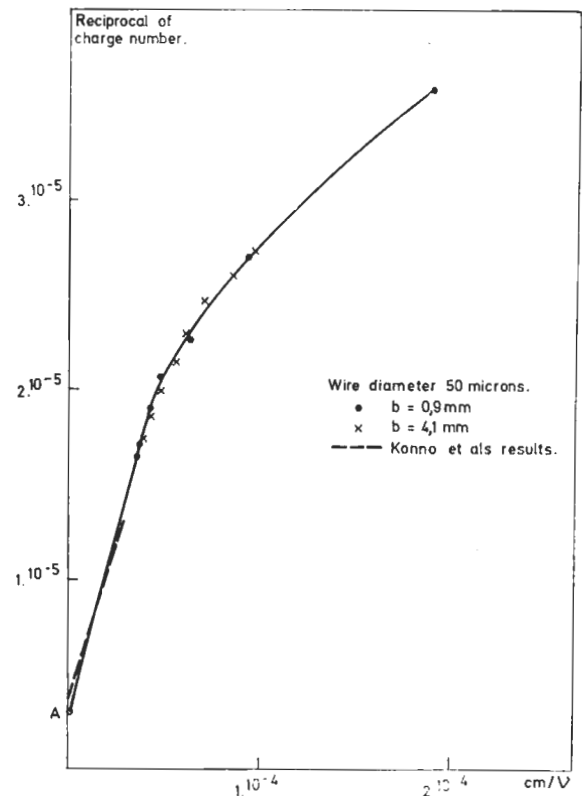


Fig. 6. Reciprocal of charge number against maximum cathode field strength.

- Two conclusions can be drawn from results a, b, c:
- Increasing the distance between the wire and the cathode allows higher fields on the wire without electrical breaks.
 - Decreasing the wire diameter allows the same amount of light for lower voltages.

4. Predicted results with gamma rays

The results acquired with the α -particles of Americium-241 may be extrapolated to the case of gamma rays. An α -particle generates an initial ionisation disappearing to a large extent by recombination. This effect diminishes while the electrical field is increased. For a field assumed to be infinite the number of charges created by an α -particle would be identical to that generated by a totally absorbed gamma ray of the same energy. Fig. 6 shows the curve of the reciprocal of the maximum number of charges versus the reciprocal of the maximum field. The point A for an infinite field has been calculated assuming 16.5 V as mean electron creation energy. A line is drawn between this point and the last measured values. The charge measurements above a certain voltage are impossible due to microbreaks while the PMT measurements remain practical. At this point the rates between the number of charges generated by a field tending to infinity and the same number estimated by extrapolation can be figured out. From this, a good guess of the signal height which

TABLE 1
Predicted results.

Case a		Case b		Case c	
V (kV)	G	V (kV)	G	V (kV)	G
6	7.2	13	9.4	8	13
		17	9.4	9	14.5

would be obtained for a gamma ray, can be done. Dividing this result by the cathode pulse height, one reaches the light gain due to electrical field. Table 1 shows the results in the cases a, b, c for various values of the high voltage.

5. Discussion

We take for the maximum field on the cathode:

$$E = - \frac{V}{\log 4b/d} \frac{2}{b}.$$

This is the field in the center of the source assuming the wire infinite. The assumption seems correct for $b = 0.9$ mm. We have shown in a dashed line the measurements of Konno et al. as found on fig. 6 of ref. 8. They seem in fair correlation to our own measurements. Nevertheless if $b = 4.1$ mm the above

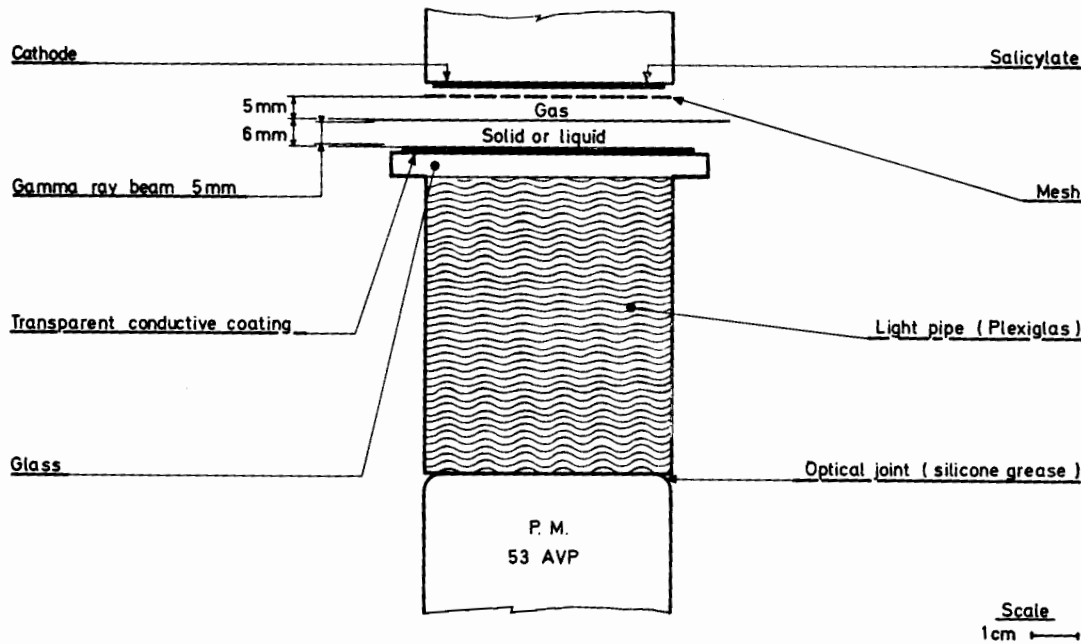


Fig. 7. Solid-gas xenon experiment.

TABLE 2
Summary of results.

Pressure (kPa)	Liquid-gas 158		Solid-gas 67		
Voltage (kV)	10	12	2.5	5	9
E_{gas} (kV/cm)	12.1	14.5	3.1	6.25	11.2
$E_{\text{I},s}$ (kV/cm)	6.5	7.8	1.5	3.1	5.6
G	110	290	2	10	42

formula for the field on the cathode is no more valid. The wire being welded on a copper ring of 13 mm inside diameter, its influence cannot be neglected any more. Under these circumstances one should use the previous curve in order to estimate the field by measuring the charge for the lowest applied voltage. The other experimental points are drawn on the curve (crosses on fig. 6). There is a good correspondence with the values obtained for $b = 0.9$ mm.

Estimating the number of photons created close to the wire is difficult. The wire screens out some of the light which is partially directed to the exit window and is partially reflected on the grinded stainless steel cathode. The number of photons emitted by scintillation in liquid xenon has been studied by various authors. It would take between 30 and 50 eV to get one photon reaching the PMT after UV to visible light conversion by means of diphenyl stilbene (D.P.S.).

6. Solid-gas xenon

6.1. MATERIAL AND METHODS

The previous device has been modified as follows: the wire is suppressed; conductive coating covers the glass-window. Salicylate is spread on the cathode and a grid is applied to it allowing charge flow. We used a collimated Cobalt-60 source (1.17 and 1.33 MeV gamma-rays). The dimensions of the beam are 150×5 mm². With this lay-out, one may directly evaluate the light gain G relative to the scintillation in absence of the electric field.

6.2. RESULTS AND COMPARISON BETWEEN SOLID-GAS AND LIQUID-GAS XENON

Table 2 summarises the results.

The electric field is calculated by using 1.85 and 2 as relative dielectric constants respectively for the liquid (E_{I}) and the solid (E_{s}). These values were estimated from Marcoux's results¹¹.

In absence of any electric field the PMT sees 1.8

TABLE 3
Multiplication factors.

	Liquid-gas			Solid-gas			
E_{g} (kV/cm)	12.1	14.7	17 ^a	3.1	6.25	11.2	12.5 ^a
M	1.5	2.7	128	1	1.6	1800	73000

^a Microbreaks.

times less light in the case of solid xenon than in the case of the liquid phase. This loss seems to be due to the light diffusing at the solid-gas interface. In our arrangement the light emitted by the salicylate must cross the interface to reach the PMT (fig. 7).

7. General discussion

The first experiments in the liquid-gas system were carried out with the α -source on the cathode, a 4 mm distance between electrodes and an approximatively 2 mm height of liquid. Under those conditions a gain of 1.4 only is reached for 4 kV high voltage and for a field in the gas estimated to be 12.9 kV/cm. The light amplification seems disturbed by the presence of positive charges in the gas. The curves of Kruithoff and Penning¹³) allowed to calculate the multiplication M as produced by the field E_{g} from table 3.

The M values calculated in the liquid-gas system do not counteract the measurements of G , they may be true. That is not the case for the solid-gas system. If M was 1800 for 9 kV, G should be greater than 42. The actual field in the gas above the solid is less than its calculated value. We think that more light from the solid-gas system may be obtained with xenon more purified and the time of solidification longer. In these preliminary experiments the solid is obtained in 2 h; the xenon is bottled back in the evening in order to avoid the use of a safety device in case of a reheating.

8. Conclusion

The results confirm the validity of our assumptions. The amount of light created in liquid xenon around 20 μ m diameter wires is sufficient to look for a better energy resolution. At a 1.5 kV/cm field electrons go from the solid xenon into the gas. A light amplification of 42 has been observed. There is reasonable hope of reaching a higher gain with a better quality solid. The experiments presently under way will allow the measurement of the energy resolution for a liquid xenon detector with collimated gamma ray sources whose energy may be below 30 keV. The solid-gas will

be prepared by controlling the temperature gradient and using a barium vapour purifier.

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