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A CYLINDRICAL PROPORTIONAL CHAMBER WITH OPTICAL READOUT

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ABSTRACT

The use of special anode-light-guides in cylindrical proportional chambers of small diameter is proposed. It seems to be an attractive possibility for detectors with a large number of channels. The gas mixtures for such a device were investigated. The problem of light emission by the different gas mixtures and the problem of bringing out the light signal are discussed.

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1. INTRODUCTION

Modern detectors based on proportional chambers (PCs) for high-energy physics may have a large number of channels, up to 10^5 . A number of serious problems concerning technological feasibility and the lifetime of PCs and front-end electronics then arise.

There are some possible solutions:

- i) To use straw chambers of ≤ 10 mm diameter. Aluminium-coated Mylar, 30–50 μm thick, can be used as the cathode material [1–4]. The advantages of such chambers are
 - a) the mechanical tolerances are less severe;
 - b) wire breakage does not kill adjacent chambers—which is often a problem with conventional PCs.
- ii) To use the optical readout of light signals [5, 6]. The signal can be amplified by an image intensifier coupled to a CCD. It is very important that CCDs and image intensifiers be commercially available [7–10].

We propose to use a special anode–light-guide [11], i.e. a conducting optical fibre having a wavelength shifter (WLS)-doped core. Such a device (fig. 1) could possibly open the way to detectors with a huge number of channels.

A few chamber constructions with optical readout [11–13] have already been developed.

We have investigated the different characteristics of a cylindrical proportional chamber with an anode–light-guide.

2. CHOOSING THE GAS MIXTURE

It is well known [10] that pure noble gases have very good electroluminescent properties, but when used in a gaseous detector they have certain disadvantages.

- i) The electron drift velocity is ~ 20 mm/ μs , which means that the detector is rather slow.
- ii) Admixtures of hydrogen, nitrogen, methane, and isobutane can increase the drift velocity, but the presence of a few per cent of such an admixture cuts the light yield sharply.
- ii) Noble gas emission spectra are somewhere in the vacuum UV region (wavelengths shorter than 200 nm). This leads to considerable losses when trying to capture light with some kind of WLS within the anode–light-guide core, owing to absorption in the conductive layer, the core cladding, and the core itself.

As demonstrated by Charpak et al. [12], the mixtures of noble gases with triethylamine (TEA) exhibit a rather high light yield. Also, these mixtures are attractive because of some other useful qualities:

- i) The emission spectrum of these mixtures lies between 280 and 290 nm. There exist a number of WLSs that match this emission extremely well, the efficiency of the WLS fluorescence process being higher than 90%.
- ii) In the wavelength range 280–290 nm, many materials (fused silica, polystyrene, etc.) are rather transparent when the layers are thin.
- iii) The vapour pressure of TEA at room temperature is 0.07 atm, thus providing concentrations of TEA that increase the drift velocities considerably.

3. TEST DETECTOR

To check the idea of using an anode–light-guide we have constructed a test chamber that allows electronic as well as optical readout (fig. 2). The chamber body is an aluminium cylinder with a 6 mm inner diameter (cathode). The chamber was irradiated through a thin aluminium window with the 5.9 keV quanta of an external ^{55}Fe source. The electric signal from the cathode goes to a charge-sensitive preamplifier. After shaping, it is fed to a multichannel analyser.

The light signal was detected by a photomultiplier (PM) tube attached to one end of the light-guide. The signal from the PM was also amplified and shaped for further analysis. For the calibration, we installed a light-emitting diode (LED) close to the PM.

The chamber was operated at a constant gas flow at normal pressure. In order to obtain different mixtures, we added TEA vapour to the controlled flows of gases.

The anode of the chamber has a composite structure, the essential part of which is a fused silica capillary. The diameters of the tested sample were 320 μm (outer) and 260 μm (inner). The outer surface of the capillary was covered with a thin layer of tin and indium oxides. The layer was obtained by cathode sputtering, and it proved to adhere well to the fused silica (this method is known to yield hard and stable layers [14]). According to our measurements, this layer is

- i) conductive, $10^5 \Omega$ per centimetre of anode length;
- ii) transparent in the wavelength range of TEA emission (around 280 nm). The measured attenuation was smaller than 20%. As mentioned above, the anode must work also as a light-guide. To accomplish this, the capillary was filled with styrene (refractive index 1.55), in which the WLS was dissolved [9]. It works as shown in fig. 3: UV light produced in an avalanche goes through the cladding and excites the WLS within the liquid core. Then light of a longer wavelength is emitted isotropically, and is partially trapped in the core owing to the difference in the

refractive index of the core and of the fused silica cladding. In our case, some 3% of light is trapped and transported to the end of the light-guide where the PM is installed. The percentages of trapped light for some cores and claddings are presented in table 1.

Two types of WLS were tested:

- i) p-terphenyl + POPOP: The absorption spectrum of p-terphenyl matches well with the emission spectrum of TEA (fig. 4); the efficiency of the WLS fluorescence is 95% [13]. We chose a concentration of about 1.4%. The calculated attenuation length of TEA emission in the core doped with 1.4% of p-terphenyl is less than 10 μm (extinction coefficient borrowed from ref. [15]). At the same time, the attenuation length of TEA emission in the core material itself (styrene) is about 100 μm . The introduction of 0.04% of secondary shifter—POPOP—led to the efficient capture of p-terphenyl emission (with a capture length $\leq 100 \mu\text{m}$) and to efficient (95%) emission in still longer wavelengths (see also fig. 4). At this POPOP concentration, the core is still very transparent, as shown in ref. [16]. Fused silica/styrene light-guides doped with p-terphenyl and POPOP have an attenuation length of about 80 cm.
- ii) 1,5-diphenyl-3-mesityl-2-pyrazoline (DPMP): This substance, which is chemically similar to PMP, is a very promising WLS for plastic scintillators [17]. The outstanding feature of this WLS is the unusually wide gap between the absorption and emission spectra (fig. 5), which makes it possible to obtain superb efficiency and transparency (secondary shifter not used) at WLS concentrations of several per cent.

As the distance between the avalanche and the PM was only 3 cm, the signal attenuation in the light-guide was considered to be negligible.

4. SOME RESULTS

We have investigated the following characteristics of gas mixtures:

- i) the dependence of the light yield (number of photoelectrons in the PM tube per 5.9 keV quantum absorbed in the chamber volume) on the high voltage (HV) applied to the anode;
- ii) the dependence of the gas gain on the HV;
- iii) the effect that the type and amount of molecular admixture in a noble gas has on the light yield;
- iv) the spectroscopic qualities of the detector.

Figure 6 shows the dependences of the light yield and gas gain on the HV for a mixture of Xe (90%) + TEA (5%) + isobutane (5%). At a gas gain of 5×10^3 the light yield was 100 photoelectrons per 5.9 keV quantum.

Similar measurements have been carried out for a number of mixtures (Ar, Kr, He). Their characteristics are shown in table 2, where light yields are presented (relative to that of the above-mentioned mixture) at a gain of 5×10^3 . We found that the shapes of the optical signals for all mixtures were identical: a leading front of 20 ns and a long tail (decay time 50 ns).

The light yield of pure Xe was relatively small: obviously this is due to the absorption of UV light, produced in the decay of Xe^* excited molecules (in the 170 nm range), by the conducting layer on the anode surface. The absorption in the styrene core is considerable for 170 nm. With pure Xe, the charge signal for the energy resolution was 25% (FWHM). The chamber operated at gains of up to 10^4 without breakdown.

Adding TEA vapour to xenon somewhat spoiled the resolution and made the maximum gain smaller (10^3 before breakdown occurred). The situation improved when a few per cent of isobutane was added: the resolution in the charge signal became 20% and the maximum gain 2×10^4 . Isobutane did not spoil the light yield at concentrations of up to 30%. At higher percentages, the light was cut, as well as the trailing edge of the signal. Thus, adding a few per cent of isobutane gives the mixtures a high light yield and a high drift velocity. The total electron collection time in the chamber gas (cathode diameter 6 mm) was less than 100 ns with Xe + TEA (5%) + isobutane (20%). Figure 7 shows the light yield as a function of TEA concentration.

One can estimate the total number of photons emitted into the full solid angle by one electron in an avalanche (parameters such as the solid angle, the photocathode efficiency, the amount of light trapped in the light-guide, etc., are known). A simple calculation for an argon mixture gives

$$n = 0.2 \text{ photon per electron in the avalanche.}$$

The corresponding value for imaging chambers is one photon per electron [12]. This is probably because in avalanche detectors the electrons undergo a bigger potential difference (the gas mixtures are of the same type).

From the data of ref. [11] the corresponding value for pure xenon can be estimated as 1.5 photon per electron. Thus one can see that a TEA admixture cuts the total number of electroluminescence photons by an order of magnitude (at the same gain).

Breakdown always occurred at a gain of 2×10^4 . We did not find any dependence of this value on the gas mixture composition. Special measurements proved that the most

probable cause of breakdown was the growth of streamers of dimensions comparable to the distance between the anode and the cathode. When we changed the anode diameter to 100 μm (gold-plated tungsten), the breakdowns were not observed, even at gas gains greater than 2×10^4 , but we observed some signals of amplitudes that were an order of magnitude greater than usual. When the HV on the anode was higher, the percentage of such pulses increased. The chamber then operated in self-quenching streamer discharge mode [18].

After some investigation, we decided that very stable operation without any sign of streamers is possible at gains of about 5×10^3 . At this gain we obtained 120 photoelectrons in the PM tube. The gas mixture was Xe + TEA (5%) + isobutane (20%), and the light-guide core was doped with DPMP.

5. POSSIBLE ORIGIN OF LIGHT EMISSION

The possible mechanism of light emission in mixtures of noble gases with TEA was formerly studied in ref. [19], where it is explained as being the radiative de-excitation of TEA molecules. The emission spectra of such mixtures (with organic quenchers) are quite similar to the emission spectrum of pure TEA vapour.

Excited TEA molecules originate from

- i) direct excitation by electrons drifting in a strong electric field:

- ii) capture of the excitation energy of the atoms (molecules) of a noble gas by TEA:

isobutane is transparent for wavelengths greater than 175 nm [19], the only process that can cause this shortening is

The estimated cross-section of this non-radiative process is 10^{-16} cm^2 .

6. PROBLEMS OF BRINGING OUT THE LIGHT SIGNAL

All the light yields (see table 2 and fig. 6) were measured directly at the end of the active anode-light-guide. It is likely that the image intensifier might not be placed just near the detector (because of possible magnetic fields etc.). When the light signals are transferred to remote light detectors, some losses are inevitable. These are

- i) losses at the connection point between the active anode and the transport fibre;
- ii) losses due to attenuation in the transport fibre.

The total amount of the light trapped within the anode is proportional to the capture coefficient (see table 1). The advantage of having a light-guide with a large aperture (i.e. having a big difference between the refraction indices of the core and the cladding) is lost when the light-guide has to be connected to a low-loss transport fibre having, in general, a narrow aperture. Wide-aperture polystyrene fibres clad with a silicon compound have a typical attenuation length of something like 2 m [24] for a wavelength of 420 nm.

In our case, the fused silica fibres coated with a silicon compound ($l_{\text{att}} = 100 \text{ m}$; 40 dB/km) hold some promise [25]. The capture coefficient is then 0.02 (table 1).

Taking into account the difference between the refraction indices of silica and styrene, the narrowness of the aperture, and the losses in the transport fibre (100 m), the total attenuation will be at least 8 dB, which corresponds to 20 photoelectrons per 5.9 keV photon absorbed in the chamber gas (with the mixture Xe + TEA (5%) + isobutane (20%), gain 5×10^3 , core doped with DPMP) or to 35 photoelectrons under the same conditions with the mixture Ar + TEA (5%) + isobutane (20%).

7. HOW TO BOOST THE SIGNAL

There seem to be two ways of boosting the signal:

- i) by decreasing the anode diameter;
 - ii) by using a series of focusing elements.
- i) If the anode diameter were to be decreased, at the same gain, then the relation E/p in the anode vicinity would be higher. So a number of production mechanisms

for excited TEA molecules would go into effect. It is also very likely that the light yield would increase. Furthermore, using thin anodes would allow operation at gains substantially higher than at present (up to 5×10^4).

- ii) It might be useful to use tiny focusing elements such as those now being widely employed in fibre optics [27]. With their help, a junction can be made with minimal losses.

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Table 1
Capture efficiency K of the active anode
for some core and cladding materials

Core Cladding	Refractive index	K
Styrene	1.55	0.03
Silica	1.46	
Polystyrene	1.60	0.045
Silica	1.46	
Polystyrene ^{a)}	1.60	0.19
Air	1.90	
Polystyrene	1.60	0.06
Si compound ^{b)}	1.40	
Si compound	1.40	0.02
Silica	1.46	

a) Attenuation length about 3 to 5 cm.

b) Silicon compound cladding of some optical fibres.

Table 2
Relative light yields of several gas mixtures, each with 5% TEA and 5% isobutane,
for different core types ('-' means that no measurements were made)

Core	Main component (90%) of the mixture				Pure Xe
	Xe	Ar	Kr	He	
Styrene + 1.4% p-terph. + 0.04% POPOP	1	1.7	1.7	0.7	-
Styrene + 5% DPMP	1.3	-	-	-	0.2
Polystyrene + 1.5% p-terph. + 0.01% POPOP	0.6	-	-	-	-

Figure captions

Fig. 1 Schematic view of a multichannel detector based on straw chambers with optical readout.

Fig. 2 Schematic cross-section of test chamber:

- 1 - body
- 2 - insulator
- 3 - active anode (light-guide)
- 4 - WLS-doped liquid styrene
- 5 - very thin glass plate
- 6 - indium contact
- 7 - photomultiplier
- 8 - epoxy resin

Fig. 3 Principle of operation of the active anode-light-guide.

Fig. 4 Spectra of the various WLSs and of the TEA [13, 19].

Fig. 5 Spectra of PMP [17] and TEA.

Fig. 6 a) Dependence of light yield and gas gain on the HV applied to the anode. The shape of the light signal is shown in the upper left-hand corner.

b) Dependence of energy resolution (for light and for charge signals) on HV.

Fig. 7 Light yield as a function of TEA concentration [mixture Xe + isobutane (5%) + TEA].

Fig. 8 Conversion efficiency of TEA as a function of the UV wavelength [21].

Fig. 9 Dependence of the light yield of the mixture Xe + He + TEA (5%) + isobutane (5%) on Xe percentage.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9