DEVELOPMENT OF HIGH PRESSURE XE SCINTILLATION PROPORTIONAL COUNTER FOR EXPERIMENTS IN "LOW-BACKGROUND" PHYSICS.

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Abstract

Characteristics of a scintillation proportional counter with WLS fiber optics read-out is described. The possibility of detection of the proportional scintillation signal produced by the single electron of primary ionization is shown. The counter can be applied for the experiments in "low–background" physics which require a low energy threshold.

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1 Detector

A detector with a very low energy threshold and a significant mass of working substance is actual now for the modern experiments in "low–background" physics such as a detection of the weakly interacting particles of dark matter in the Universe [1, 2, 3, 4] and measurement of neutrino magnetic moment with the use of artificial neutrino source [5].

We investigate an original method of readout for gas scintillation proportional counter which was not used earlier, although it is based on a combination of the known physical phenomena studied in many world laboratories [6]. This method gives one the new possibility to utilize high pressure gas proportional counters for the experiments mentioned above.

With respect to proportional counter with an electrical signal readout a scintillation proportional counter has the following basic advantages:

– An equivalent electronic noise is \(5 - 10\) times lower owing to the use of a PMT as a low–noise device.
– Theoretical limit of energy resolution is lower.
– There is no microphonic noise.
– A HV circuit and spectrometric electronics are totally decoupled from each other.

The detector is being a cylinder volume with a central anode wire surrounded with an array of fibers (Fig. 1).

The electrons originated from ionization of the working medium (Xe) are collected on the central anode of the detector, where the process of avalanche multiplication (gas gain) takes place. An excitation of Xe molecules with subsequent emission of the ultraviolet photons (\(\sim 170\) nm; electroluminescence or proportional scintillation) take place simultaneously. The photons are coming on the first–stage converter (or wavelength shifter; WLS; p–terphenyl) deposited on the fiber surface and then re–emitted in the waverange of a soft ultraviolet. These photons penetrate into the fiber core, where they are absorbed by the secondary–stage converter (POPOP) and re–emitted again in the blue wavelength range, where a PMT possesses a maximum sensitivity and a fiber has a maximum transparency.

The gas gain is supposed to be a few units of \(10^3\). With this value the total light gain (gas gain with electroluminescence) will be \(\sim (0.5 - 1.0) \times 10^4\) UV–photons per one electron of primary ionization (one free electron in the detector sensitive volume).

For the light collection with WLS fibers the efficiency can be obtained to be \(\sim 0.006\) phe/UV–ph (photoelectrons per one UV-photon) [3]. This relatively low value is caused by a low efficiency of light capture in a fiber (\(\sim 0.07\)) and a low quantum efficiency of a PMT.
photocathode (∼0.15). Nevertheless, owing to the use of the dual multiplication (gas gain + light gain) near the anode one can obtain a unique yield of ∼ 400 - 500 phe/keV and therefore, the sensitivity to the SINGLE free electron originated in the detector.

The division of the fibers into groups with the PMT pairs viewing fibers from opposite ends operating in coincidence and majority coincidences between the groups of fibers will allow one to exclude totally the noise of photomultipliers and electronics and to lower the energy threshold of triggering down to the level corresponding the energy necessary for origination of several electrons of primary ionization.

The detector on the basis of high pressure (up to 20 atm) gas scintillation proportional counter with a new method of signal readout can be competitive with low–temperature bolometers being developed now for dark matter search because it has low energy threshold and can exceed they by mass (it can be up to a few tens of kilograms). This method also opens the possibility to carry out a unique experiment on neutrino magnetic moment search with the use of the low–energy antineutrino tritium source. For this experiment a massive detector having a low energy threshold (< 1 keV) is required.

Xe is chosen as a working medium owing to the following reasons:

− It has the high cross section of spin–independent interaction (because of the large number of nucleon in the Xe nucleus) and also the isotopes with a spin 1/2 (129Xe; 26.4%) and 3/2 (131Xe; 21.2%) in the natural Xe, which take part in spin–dependent interaction with dark matter particles.
− There are no long–life radioactive isotopes.
− High degree of purification of large amounts from radioactive contamination is possible.
− It has high cross–section of absorption of the low–energy photons (E < 20 keV). This fact allows one to reject effectively the characteristic emission of the detector body by means of the near–wall active layer of gas (with its own cathodes and anodes, as shown in Fig. 1).

2 The use of fiber optics for readout of electroluminescence in the Xe based detectors

Photons of primary and secondary scintillation (electroluminescence) in Xe have the short wavelength of 170 nm and can be detected by means of an ultraviolet photomultiplier or usual PMT with a wavelength shifter (WLS). The first use of optical WLS fibers for this aim was described in (see above). Fibers was utilized for original solution of a complicate technical problem of the readout of electroluminescent signal in a high pressure gas detector and obtaining the event coordinates. The WLS fibers was coated with the p–terphenyl by means of vacuum deposition. The possibility of the use of WLS fibers for detection of an electroluminescent ultraviolet signal is considered in the ICARUS collaboration. The fibers are proposed to be located in a LXe and VLPCs possessing a high quantum efficiency (∼ 80%) to be used for signal readout. Such a combination (fiber and VLPC) allows one to achieve the high value (∼ 10^{-2}) of photoelectron yield per one UV photon.

We propose to use WLS fibers in a long cylindrical high pressure gas proportional counter for detection of the electroluminescence at the central anode. Preliminary study of the detection efficiency of fiber was carried out with the setup schematically shown in Fig. 2.
The 40–cm long scintillation fiber with a diameter of core (p–terphenyl + POPOP) of 0.8 mm and a cladding diameter of 1 mm was used. One end of the fiber was coupled with the central part of the FEU–85 PMT (without optical contact). The PMT current was measured.

Ultraviolet photons (170 nm) was emitted from the special UV source on the basis of gaseous Xe, radioactive source, and MgF₂ window. Since ultraviolet light with such a wavelength is totally absorbed in the cladding of the fiber two versions of light re–emission before entering the cladding (Fig. 2a and Fig. 2b) was tested. In the case (a) the WLS of the first stage (p–terphenyl) was deposited in vacuum on the fiber surface. In the case (b) the WLS was deposited on the transparent Mylar film located near the fiber. The photons re–emitted at the first stage penetrate into the core where re–emitted again by the secondary WLS (POPOP). Since the p–terphenyl coating is mat the process of light transportation to the photodetector takes place in the first case only at the core–cladding interface while in the second case, at both surfaces. Taking this into account one can explain the behavior of the distance–efficiency curves for both cases shown in Fig. 3 in relative units. The fiber uncoated with a WLS possesses a significant nonuniformity (squares) since the outer surface of it is of insufficient quality.

3 Energy resolution and light gain of electroluminescent detectors

The use of electroluminescence (proportional scintillation) attracts an attention of elaborators of gas proportional detectors owing the possibility to obtain a significant internal light multiplication resulting in better signal–noise ratio than for electrical readout of signal (with gas multiplication) owing to the use of a PMT as a low–noise device. In addition, a proportional scintillation counter also shows better energy resolution in the multiplication mode with low or unit gas gain [10].

The energy resolution of a scintillation proportional counter operating in the mode of gas multiplication is defined with a fluctuation of the following values: the number of electrons of primary ionization, the gas gain, and the number of photoelectrons:

\[
\frac{\sigma_E}{E}^2 = \frac{F}{N_e} + \frac{f}{N_e} + \frac{1}{N_{phe}}
\]

where:

\(F\) is Fano factor, \(f\) is a factor describing a fluctuation of the gas gain [11], \(N_e\) is a number of electrons of primary ionization, \(N_{phe}\) is a number of photoelectrons.

Taking into account that \(N_{phe} = kN_e\) the energy resolution can be written as following:

\[
\left(\frac{\sigma_E}{E}\right)^2 = \frac{1}{N_e}(F + f + \frac{1}{k})
\]

where \(k = k_L\varepsilon Q\) is a coefficient of transformation (that is the number of photoelectrons per one electron of primary ionization), \(k_L\) is a light gain, \(\varepsilon\) is an efficiency of light collection to the photocathode, \(Q\) is a photocathode quantum efficiency. The value of Fano–factor for Xe is from 0.15 to 0.17 [12], the value of \(f\) is about 0.5 and 0.7 – 0.8 for the value of gas...
gain of $\sim 10$ and $> 10^2$, respectively \cite{11}. Therefore, it is clear that at $k > 5$ the energy resolution is defined mainly with the gas gain fluctuation. To improve the energy resolution of a scintillation proportional counter one have to reduce the gas gain down to the minimal possible value keeping $k$ constant. The last is achieved by increasing the light collection efficiency $\varepsilon$ and quantum efficiency of a photodetector $Q$. Another way is optimization of the wire diameter to obtain a maximum contribution of the electroluminescence taking place outside the avalanche region to the total light gain.

The number of photons created by the single electron per unit of length is calculated according to the semi–empirical formula:

$$\frac{dW_{ph}}{dx} = 70(E/p - 0.8)p[cm^{-1}]$$  \hspace{1cm} (3)

where:

$E$ [kV/cm] is an electric field strength, $p$ [atm] is a pressure.

Then the light gain for a gas counter of cylindrical geometry (without gas gain) can be calculated as following:

$$k_L = \frac{70U_a}{\ln(R_c/R_a)} \int_{\tilde{R}_a}^{r_{thr}} \frac{dr}{r} - 56\int_{\tilde{R}_a}^{r_{thr}} dr$$  \hspace{1cm} (4)

where:

$U_a$ [kV] is an anode potential, $R_c$, $R_a$ [cm] are cathode and anode diameters, respectively, $r_{thr}$ is obtained from the relation:

$$\frac{U_a}{r_{thr} \ln(R_c/R_a)} > 0.8$$  \hspace{1cm} (5)

4 Experimental tests with the prototype

The prototype described in \cite{13} and shown in Fig. 4 was built to study characteristics of a scintillation proportional counter with fiber optical readout. A fiducial length and an inner diameter of the counter are 25 cm and 2.2 cm, respectively. The fibers with a total number of 72 are located near the inner surface of the cylindrical wall. The ends of the fibers are brought together in a wisp near the glass window having a diameter 1.5 cm. A PMT of FEU–85 type is placed behind this window outside the Xe volume. The 70 $\mu$m stainless steel cathode wires form a right octagon and located at a distance of 1.1 cm from the cylinder axis. The cathodes have a potential equal to that of the counter wall. The gilt tungsten anode wire with a diameter of 50 $\mu$m is stretched along the cylinder axis. A radioactive source $^{241}Am$ is put on the inner wall surface at a distance of 5 cm from the end of the counter.

The prototype is designed for the gas pressure of up to 8 atm. The value of pressure is restricted by a strength of the optical window used. Gas filling of the counter was performed through an "Oxisorb" purifier. Since a constant circulation and purification of the gas was
not provided gas refreshing in the counter was performed by means of refreezing it back to
the storage cylinder and passing it again through the "Oxisorb".

The scheme of electronics is shown in Fig. 5. A readout of an electrical signal from the
wire was performed by means of charge-sensitive preamplifier in parallel with electrolumi-
nescent readout. The PMT signal passed through the circuit of discrimination and selection
which rejects the pulses with a duration $T < 250$ ns is used as a trigger. Both signals
are digitized by means of charge-to-digit converters. A light pulse from the light emitting
diode (LED) coupled with the photocathode of PMT through an optical fiber is used for
calibration.

5 Experimental results

The pulse height spectra measured with $^{241}\text{Am}$ radioactive source at a pressure of 2 atm and
$U_a = 2.9$ kV for the electroluminescent and electrical readout are shown in Fig. 6 and Fig.
7, respectively. It is seen from these spectra that both channels are totally equivalent each
other, the energy resolution for each case is the same ($13\%$ (FWHM) for 13.9 keV and $12\%
for 17.8$ keV). The yield of photoelectrons is obtained to be 450 phe/keV, and thus, the $k =
11$ photoelectrons per one electron of primary ionization. According to (2) for such value of $k$
the resolution to be $10\%$ at 13.9 keV. The worse value of energy resolution can be explained
by possible nonuniformity of the wire diameter. Fig. 8 shows the pulse height spectrum
obtained for the electroluminescence channel at a pressure of 8 atm, the energy resolution
is $13\%$ at 13.9 keV. A low–energy part of the spectrum ($< 15$ keV) specially measured at
8–atm pressure is shown in Fig. 9. The maximum value of a photoelectron yield achieved
at a pressure of 8 atm is 230 ph e/keV. It is seen from Fig. 9 that with the triggering mode
used (single PMT + time selection of pulses) the energy threshold can be set at a level of
0.2 keV.

To demonstrate the possibility to lower the energy threshold down to the level corre-
sponding the energy necessary for origination of several primary electrons we have shown
experimentally the detection of the single electroluminescent pulse, which corresponds to the
process of avalanche multiplication caused by a single electron. For this aim we used the
feedback pulses coming after the main pulse. In our case at a pressure of 2 atm and $k=7$
the main pulse was accompanied with a sequence of feedback pulses having a period equal
to the electron drift time from the cathode to the anode ($\sim 8$ $\mu$s) and a ratio of heights of
neighboring pulses of 1:10. Therefore, the pulse appearing after the main pulse at the time
corresponding, for example, to the 6-th feedback pulse must be knowingly a single–electron
one. Fig. 10 shows the pulse height spectrum (2) for such signals. The signals with a total
duration of more than 120 ns was selected. This value is higher than that of the noise (single–
photoelectron) signals. The pulse height spectrum of the signals from the PMT operated in
a single–photoelectron mode and triggered by the LED signal is shown in the same figure
(1). The average number of photoelectrons in the single–electron electroluminescent pulse is
obtained to be $7 \pm 1$.

Fig. 11 shows the light gain and gas gain as a function of applied voltage for pressures
2, 4, and 8 atm. The experimental data are obtained with $\alpha$ and $\gamma$–peaks at 2 and 4 atm
while at 8 atm, only with $\gamma$–peaks since at this pressure $\alpha$–particles don’t reach the sensitive
The value of light collection efficiency $\varepsilon$, which is necessary for obtaining the value of light gain, was estimated from fit with the formula (4) of the experimental points measured at such values of applied voltage $U_a$ when the gas gain is low ($< 5$) or zero. It is obtained to be $(0.6 \pm 0.1) \times 10^{-3}$ ph e/photon. Note that this value can be increased really by a factor of $3 - 4$ by means of more compact disposition of fibers, well matching of spectral characteristics of the first and second stage wavelength shifters and photomultiplier, individual selection of PMTs with a high quantum efficiency, and readout of light signal from both ends of fibers.

The experimental data demonstrate that both light gain and gas gain as a function of the anode voltage have the same exponential behavior at the tail (gas gain $> 10^3$). It is the evidence that the electrons born in the avalanche give the main contribution to the light gain in spite of the fact that their path length is very short (about of several tens of $\mu$m). This fact accounts for an equal energy resolution obtained both for light and charge readout (see Fig. 6 and 7) because the photoelectron statistics is defined mainly by the statistics of electrons in the avalanche.

6 Conclusion

It is shown that with the method of signal readout by means of WLS optical fibers the value of $k \sim 5 - 10$ (photoelectrons per one primary electron) can be obtained for a high pressure Xe gas proportional counter with a cylindrical geometry and having significant sizes. Thus, the efficiency of light collection is sufficient for the photoelectron statistics to be defined mainly by the statistics of electrons in the avalanche.

The value of photoelectron yield of $> 200$ phe/keV is obtained for the pressure of up to 8 atm. This fact allows one to obtain for such detectors a low energy threshold ($< 1$ keV) owing to a low noise level of photomultiplier.

For the energy resolution of the scintillation proportional counter to be better than that of a proportional counter with electrical readout it is necessary to enhance the contribution to the light gain of the electroluminescence taking place before the beginning of avalanche multiplication process. This can be achieved, as it is seen from Fig. 11, by means of reduction $U_a$ (with making $\varepsilon$ higher) and increasing a pressure.

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FIGURE CAPTIONS

Fig. 1. Layout of electrodes and fibers inside the cylindrical body of the counter. 1 – counter body, 2 – WSL fibers, 3 – wire anodes, 4 – wire cathodes, 5 – central anode.

Fig. 2. Scheme of the WLS fiber tests. The wavelength shifter is deposited on the fiber (a); on the Mylar film (b). 1 – core, 2 – cladding, 3 – wavelength shifter, 4 – light collimator, 5 – UV source, 6 – PMT, 7 – current meter.

Fig. 3. Light collection efficiency of the fiber irradiated by 170 nm light versus the distance from PMT. Triangles and squares are corresponded to the cases (a) and (b) of Fig. 2, respectively.

Fig. 4. Schematic diagram of the prototype. 1 – fibers, 2 – cathode wires, 3 – anode wire, 4 – glass window, 5 – $^{241}$Am source.

Fig. 5. The scheme of electronics. G1, G2 – fine tuning generators, LED – light emitting diode, INV – invertor, FA – fast amplifier, CSP – charge – sensitive preamplifier, DL – cable delay line, D/S – discrimination/selection unit, M – the monostable, AC – anticoincidence circuit, D – delay ($T_{dr}$), ADC1, ADC2 – charge–digital converters.

Fig. 6. Pulse height spectrum obtained with $^{241}$Am source via electroluminescence channel; $P = 2$ atm, $U_a = 2.9$ kV. 1 – pedestal, 2 – $L_\alpha$ Np (13.9 keV); 3 – $L_\beta$ Np (17.8 keV); 4 – $K_\alpha$ Xe (29.8 keV), 59.6 keV – $K_\alpha$ Xe (29.8 keV).

Fig. 7. Pulse height spectrum obtained with $^{241}$Am source via charge–collection channel at $P = 2$ atm, $U_a = 2.9$ kV. 1 – pedestal, 2 – $L_\alpha$ Np (13.9 keV); 3 – $L_\beta$ Np (17.8 keV); 4 – $K_\alpha$ Xe (29.8 keV), 59.6 keV – $K_\alpha$ Xe (29.8 keV).

Fig. 8. Pulse height spectrum obtained with $^{241}$Am source via electroluminescence channel at $P = 8$ atm, $U_a = 5.5$ kV. 1 – pedestal, 2 – $L_\alpha$ Np (13.9 keV); 3 – $L_\beta$ Np (17.8 keV); 4 – $K_\alpha$ Xe (29.8 keV), 59.6 keV – $K_\alpha$ Xe (29.8 keV).

Fig. 9. Low-energy part (< 15 keV) of the pulse height spectrum measured at 8–atm pressure.
Fig. 10. Pulse height spectra measured in a single-electron mode (2; $U_a = 2.9$ kV, $P = 2$ atm) and in a single-photoelectron mode (1; $U_a = 0$).

Fig. 11. Light gain and gas gain as a function of applied voltage at a pressure of 2, 4, 8 atm. LG is light gain, GG is gas gain, curves – fit with formula (4).
