Characteristics of proportional counter filled with CF$_4$ and Xe additions

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In this article the measurement results of proportional counter working characteristics filled with CF$_4$ and Xe (0 $\div$ 5% Xe) additions at different pressures (0.8 $\div$ 14.8 at) are presented. We have found that a bit of Xe addition reduces working voltage necessary to get the same gas amplification by two times against pure CF$_4$; it improves as well the resolution of the counter and increases limit gas amplification by more than ten times.

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The multicell proportional counter (MCPC) designed to search for weakly-interacting massive particles (WIMP) was proposed in [1], and is similar to the counter described in [2]. The suggested experiment belongs to the class of experiments aimed at the direct detection of WIMP. To the same class of experiments belong recent experiments with cryogenic, semiconductor and scintillation detectors [3-5]. In such experiments the nuclei recoil energy is detected after interaction of WIMP with nuclei. The expected energy-release is equal to few keV in our experiment. It is reasonable to measure such energy-release with help of high-resolution proportional counter.

One of the possible candidates for dark matter particle is neutralino – the lightest stable particle suggested by supersymmetry. It has spin $s = 1/2$ and can interact spin-dependently with target nuclei with non-zero spin. The intensity of spin-dependent interaction is more significant for light elements, such as $^{19}$F ($I = 1/2$, 100% isotope abundance) [6]. The proper working gas with high content of $^{19}$F for MCPC is CF$_4$. CF$_4$ is inflammable and not toxic. The drift velocity of the electrons in CF$_4$ is high even under not high electric field [7]. Due to last property CF$_4$ is widely used in the detectors intended to detect high flux of particles in accelerator experiments [8]. Moreover, CF$_4$ can be used with different gas additions [9,10]. CF$_4$ is a scintillator, which emits light in the region from ultraviolet (near 160 nm) to visible light, and has about 16% of Xe scintillation efficiency (s. e.) [11,12]. Since pure CF$_4$ is transparent for its own ultraviolet photons, it seems problematical to get high gas amplification in proportional counters since the photons generated in electron avalanches stimulate photoeffect on the cathode. The additions of isobutene or ethane increase a limit of the gas amplification (GA) by few times [11]. Those results are generally reached for pressures less than 1 at. The characteristics of time-project chamber filled with pure CF$_4$ at pressure 5 bar are presented in [12]. The comparison of peak positions of 5.9 keV signal amplitude distributions which correspond to two different distances between source and proportional chamber grid allowed to estimate drift length of the electron to be equal to $9 \times 10^{-3}$ m (electric field strength 600 V/cm). Authors found that the reason for bad resolution (100%) caused drift field distortion near $\gamma$-source surface. The source is placed at a butt-end of the thin (3 mm) shift binder. The majority of photons are absorbed near the source surface, because the attenuation length of the 5.9 keV photons is $\approx 1.5$ cm in CF$_4$ at pressure of 5 bar. Summary resolution of 364 and 388 keV electrons from conversion electron source $^{113}$Sn equals 25% (drift length $\approx 5$ cm). The resolution of 5.9 keV photon source equals 50% at 1 bar pressure. MUNU collaboration has obtained results allowing to build a detector aimed at the search for neutrino magnetic moment in antineutrino - electron reactor experiment. The detector is 1m$^3$ time project chamber filled with CF$_4$ at pressure of 3 bar. The transparent chamber vessel is placed into the tank filled with liquid scintillator used as active shield. In this case CF$_4$ has a number of advantages against other gases. It has high specific density (3.68 g/l) and high electron density ($1.06 \times 10^{21}$) at pressure of 1 bar. The absence of high Z elements decreases the multiple electron recoil scattering as well as distortion of its trajectories. Moreover the absence of free protons excludes the background reaction ($\overline{\nu}p \rightarrow e^+n$). Photomultipliers scanning liquid scintillator simultaneously detect scintillations in CF$_4$. The exploitation experience of this detector has shown the possibility to use such a construction as a solar $pp$-neutrino detector with threshold about 100 keV [13]. In our case, the MCPC must have threshold in the region of about one hundred eV. To have such threshold we need gas amplification of about 104. The pressure of CF$_4$ must be high enough to have large mass of the target. The experience of low background measurements with high-pressure proportional counters [14] shows that main components of non-ionization background are micro discharges and current leakage along the isolator surface in high - voltage circuits. The intensity of this component depends essentially on the mode and magnitude of the voltage supplied to a counter (on anode or cathode). In case of MCPC the voltage is supplied to anodes. The signals are read out from anodes through high voltage capacitors. Since for this case we have high intensity of non-ionization background component we need the conditions at which the voltage is the smallest for a necessary gas amplification. The latter is possible if we decrease the anode diameter and find the best addition to
In this article the proportional counter (PC) characteristics are presented. The counter was first filled with pure CF$_4$ and later CF$_4$ with Xe addition at pressures ranging from 0.8 at up to 14.8 at.

**MEASUREMENT's CONDITIONS**

The cross section of our PC is shown in fig.1 PC has stainless steel high-pressure cylindrical body with inner diameter $D = 39$ mm and wall thickness of $3$ mm. Tungsten cathode wires ($D = 0.051$ mm) are stretched along the side of a hexahedron parallel to the axis. The high-quality gilded tungsten ($D = 0.01$ mm) wire is used as anode. On the whole the inner counter is just one sample of 61 cells at the MCPC. The fiducial length of PC is $17.2$ cm, total volume $-300$ cm$^3$, fiducial volume $-32$ cm$^3$.

PC was calibrated with $56.6$ keV line of $^{241}$Am source placed on the PC’s body. The positive high voltage is on the anode. The signals are read out off anode through high voltage separating capacitor by charge sensitive preamplifier (CSP) and sent to the MCA through the shaping amplifier. The dependence of amplitude of the impulse from voltage anode. The signals are read out off anode through high voltage separating capacitor by charge sensitive preamplifier.

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The purification of the gas from electronegative admixture has been realized in flow - type procedure in the reactor (7) which consist of stainless steel pipe with absorber [15]. In our work we use CF$_4$, preliminary cleaned from electronegative admixtures up to $10^{-8}$ oxygen equivalent level [16] and industrial Xe with residual of $2 \times 10^{-6}$ of O$_2$. Before beginning our work we pumped out the set-up and PC down to $10^{-2}$ torr.

**RESULTS**

The dependence of gas amplification (GA) of PC filled with pure CF$_4$ on voltage at pressures 0.8, 1.8, 3.8, 5.8, 8.8, 12.8 at are shown in fig.3. The limitation of gas amplification for the upper part of the graphic is due to beginning of continuous discharge process. We take the ion-pair formation energy to be equal to $30$ eV for GA calculation. We read out the spectrum of 59.6 keV line of $\gamma$-source at GA≈ 500 during the same time interval at different pressures. The times of integration and differentiation are 1.6 mks for all pressures. Obtained spectra are shown in fig.4. Weak peak of 59.6 keV at 0.8 at may be explained as a result of wall effect, since the mean range of photoelectron with this energy equals to $20$ mm in CF$_4$. It is necessary to notice that PC’s volume is divided by the grid on two sections with different conditions and electric field intensity. This could possibly be the reason for the following effects: difference in the time of charge collection from these regions and difference in amplitudes of the impulse from events with the same energy release. Both effects are due to non-transparency of the grid and different time of interaction with electronegative admixture. The energy resolution for 59.6 keV line at different pressures is different, and it changes from 15% up to 25%.

Analyzing pulse shape we have found that there are after-impulses in 8 mks after main 0.5 mks-impulse. The comparative amplitude of after-impulse increases with voltage, at the same time the after-impulses of next order stay visible. The reason for this is the photoeffect on the cathode grid and wall from photons generated in electron avalanche. The comparison of delay time for impulses with calculated drift time of electrons from the cathode and the wall at $8.8$ at ($U = 2650$ V) allowed us to determine that it is generally PC’s wall that is the source.

The addition of the hydrocarbon polyatomic gas is usually used to decrease the voltage on PC and to increase the GA. In our case this addition is not useful, because it contains natural tritium ($T_{1/2} = 10.8$ y, $E = 18.7$ keV) causing additional background. The addition of CO$_2$ (20%) to CF$_4$ essentially increases the count characteristic length, increasing, however, at the same the voltage on PC [8]. It is known that small addition of the Xe to pure Ar essentially decreases voltage necessary to have the same GA as in pure Ar and increases count characteristic length [18]. The comparison of excitation energy of CF$_4$ molecules with first ionization potential of Xe allows us to suppose that addition of Xe to CF$_4$ can cause the same effect.

The dependence of GA on voltage at $8.8$ at pressure of CF$_4$ with addition of Xe (from 0% to 5%) is shown in fig.5. It is clear that small addition of Xe reduces the working voltage and increases the limit of GA by more than 10 times (upper points are limited by the working region of preamplifiers). One can find the optimal quantity of Xe analyzing the dependence of voltage on quantity of Xe in CF$_4$ at the same amplitude of impulse in fig.6. It is clear that $1 \div 2\%$ addition of Xe is best for our region of pressure. The spectra of 59.6 keV line measured during the same time interval at pressure $8.8$ at for different percentage of Xe are shown in fig.7. The spectra of 59.6 keV line for mixture with 1% of Xe at pressures from 1.8 at up to $14.8$ at are shown in fig.8. One can see the total absorption peak (59.6 keV), escape peak (29.8 keV) on Xe and characteristic lines (5 ÷ 8) of Cr, Fe, Ni at al. (elements of the wall and the wire of...
The energy resolution of 59.6 keV line equals 13.5% at 14.8 at. Note, that it is necessary to increase the times of integration and differentiation in amplifier up to 6.4 mks to have good energy resolution, although electron drift velocity decreases not more than by 2 times due to decreasing in the voltage. The reason is that in pure CF$_4$ the impulses are generally formed from single photo- and Compton electrons (point events). In the mixture CF$_4$+Xe the double-point events appear, in which the second points are caused by absorption of characteristic radiation emitted by Xe excited due to photo absorption of primary gamma-photon. In pure CF$_4$ at high pressure the contribution of double-point events also becomes evident because the probability of secondary interaction of Compton-photons is high inside PC. The above enumerated effects were confirmed by increase in energy resolution in pure CF$_4$ for 59.6 keV line from 26.6% to 8.8% at 8.8 at, when integration and differentiation times change from 1.6 mks to 6.4 mks.

DISCUSSION OF RESULTS

The increase of GA limit in mixture of CF$_4$ with Xe could be interpreted as evidence confirming the fact that Xe addition decreases essentially the probability of photoeffect on PC’s wall, caused by ultraviolet photons from CF$_4$. Those photons are generally induced by (CF$_4^+$) (CF$_4^{+\dagger}$) fragments [11] produced in a gas discharge. (It is possible, that excitation energy of the fragments is sufficient to ionize Xe atoms, or the presence of the Xe atoms prevent the formation of those fragments.)

The discovered mixture may be useful not only in our experiment for dark matter search with MCPC but for another experiments using CF$_4$ (MUNU-detector, gas detectors in accelerator experiments).

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FIG. 1. The cross section of PC

FIG. 2. The scheme of the installation: 1 - enter for gas; 2 - to the vacuum pump; 3 - thermocouple sensor of vacuum-gauge; 4 - pressure-gauge; 5 - valves; 6 - PC; 7 - reactor with Ni/SiO$_2$ absorber; 8, 11, 13, 14 - traps; 9 - flow-type traps with activated charcoal; 10 - vessel with cooling mixture; 12 - trap with activated charcoal.
FIG. 3. Dependents of GA on voltage at different pressures CF₄.

FIG. 4. Spectra of 59.6 keV line of γ-source ²⁴¹Am at different pressures of CF₄.
FIG. 5. Dependence of GA on voltage at 8.8 at pressure of CF$_4$ with addition of Xe (from 0% to 5%).

FIG. 6. Dependence of voltage on quantity of Xe in CF$_4$ at the amplitude of impulses from 59.9 keV equal to 80 mV.
FIG. 7. Spectra of 59.6 keV line measured during the same time interval at pressure 8.8 atm for different percentage of Xe.

FIG. 8. Spectra of 59.6 keV line for mixture with 1% of Xe at pressures from 1.8 atm up to 14.8 atm.