

Massive liquid Ar and Xe detectors for direct Dark Matter searches

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A novel experiment for direct searches of the Dark Matter with liquid argon double-phase chamber with a mass of liquid Ar up to several hundred tons is proposed. To suppress the β -, γ - and n_0 -backgrounds, the comparison of scintillation and ionization signals for every event is suggested. The addition in liquid Ar of photosensitive $\text{Ge}(\text{CH}_3)_4$ or C_2H_4 and suppression of triplet component of scintillation signals ensures the detection of scintillation signals with high efficiency and provides a complete suppression of the electron background. For the detection of photoelectrons and ionization electrons, highly stable and reliable GEM detectors must be used.

1. Introduction. The experiment for direct searches of Weakly Interacting Massive Particles (WIMPs) with a 100 liter Xe (Ar) double-phase chamber was proposed in [1]. The addition of trimethylamine (TMA) for detection of scintillation signals with efficiency of 35% was suggested earlier in [2]. As a result of absorption of the scintillation light, emitted by the atoms and molecules of Ar, excited in a process of recoil atom and background electron interaction, the ionization core is surrounded by a cloud of photoelectrons, the diameter of which is determined by the concentration of TMA. The detection of the ionization core and photoelectrons performed with high spatial resolution and efficiency, makes it possible to compare the ionization and scintillation signals and to highly suppress the background events.

Using of TMA as a photosensitive addition for the chamber with a large mass of liquid Ar is not possible because of slight electronegativity of the TMA molecules [2–7]. Due to that fact, the drift length of electrons in liquid Xe+40 ppm TMA, at the field of $3 \text{ kV}\cdot\text{cm}^{-1}$, is as small as 10 cm [1].

The first results on Dark Matter searches with a 2.3-litre liquid Ar chamber have been achieved in [8], where the scintillation signals are detected by photomultipliers (PMT) with an efficiency of a few percent. All inner surfaces of the chamber are covered with tetra-phenyl-butadiene wave-shifter, which is used for conversion of the VUV light into visible emission. Electrons of the ionization core are transported with electric field from the liquid Ar to the gas phase where they produce an electroluminescent light, which is detected by PMT.

The one ton liquid Ar chamber is constructed in [9], where GEM detectors, made of metalized kapton, are

proposed for the detection of electrons from an ionization core. However, using of plastic GEM detectors in long-term experiments is rather problematic due to their low reliability [10–13].

In this work it is proposed to use $\text{Ge}(\text{CH}_3)_4$ (TMG) [14] (0.15 ppm) or C_2H_4 [15] (2 ppm) as photosensitive additions to the liquid Ar of the detector. Since TMG and C_2H_4 are non-electronegative molecules, the electron drift length in the Ar+TMG (C_2H_4) mixtures may be equal to 10 meters, because these mixtures can be purified from electronegative impurities down to the level of 10^{-11} rel. vol. parts O_2 [14, 16–19]. The absorption of electrons by electronegative impurities does not change the relationship S_2/S_1 .

In liquid Ar the energy of photons $\text{Ar}_2^* \rightarrow 2\text{Ar} + h\nu$ is equal to $\sim (7.5–11.5) \text{ eV}$, while the ionization potential of TMG in liquid Ar is about 8.55 eV and for C_2H_4 it is below 9.8 eV. As a result of that, the photons emitted by Ar_2^* can ionize TMG (C_2H_4) molecules with producing of a cloud of photoelectrons around the ionization core [14] (Fig. 1).

Recoil ions, secondary and background electrons are ionizing Ar atoms by producing electron – hole pairs and excited atoms, excitons, with the following, in both cases, of self – trapped exciton luminescence, which consists of fast singlet $^1\Sigma_u^+$ component with $\tau_1 = (7 \pm 1) \text{ ns}$ and slow triplet $^3\Sigma_u^+$ component with $t_2 = (1.6 \pm 0.1) \mu\text{s}$ [8].

The ratio between the singlet and triplet intensities in liquid Ar [8] is equal to

$$I_s/I_t = 0.3(e^-), 1.3(\alpha), \text{ and } 3(\text{nr}). \quad (1)$$

For suppression of the electron background in some works (see Table) the criterion F is used:

$$F = I_s/(I_s + I_t). \quad (2)$$

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The name of project	The target of detector	The detection method	The threshold of detection	The method for background suppression	Ar ³⁹ concentration in Ar	The expected result
“ArDM” A. Rubbia [9]	Ar 1000(850) kg double-phase	$S_2/S_1 + F$ PMT+GEM	$E_{nr}^{\min} = 30$ keV	$S_2/S_1 + F$	10^2 decays/t·s	$\sigma(\text{WIMP}) = 10^{-45}$ cm ²
“MiniClean” Los Alamos [20]	Ar liquid 500(150) kg single-phase	F 92 PMT	$E_{nr}^{\min} = 30$ keV $M^{\min}(\text{WIMP}) = 20$ GeV	F	10^3 decay/t·s	10^{-45} cm ²
“Deap-3600” Los Alamos [20]	Ar liquid 3600(1000) kg single-phase	F 266 PMT		F	10^3 decays/t·s	10^{-46} cm ²
“Clean” Los Alamos [20]	Ar liquid 40(10) tons single-phase	F PMT	$M^{\min}(\text{WIMP}) = 60$ GeV	F	$< 10^2$ decays/t·s	$6 \cdot 10^{-47}$ cm ²
“Darvin” [21]	Ar 20(10) tons double-phase	$S_2/S_1 + F$ avalanche photodiodes+GEM	$E_{nr}^{\min} = 30$ keV	$S_2/S_1 + F$ K suppression= 10^8	< 40 mBq/kg	$4 \cdot 10^{-48}$ cm ²
	Xe 8(5) tons double-phase	$F + S_2/S_1$ avalanche photodiodes+GEM	$E_{nr}^{\min} = 10$ keV	$S_2/S_1 + F$ $K = 10^3$	10^{-4} decays/kg·day·keV	
Los Angeles Dr. D. Cline [22]. (proposal)	Ar 580(500) tons double-phase	S_2/S_1 12000 avalanche photodiodes	$M^{\min}(\text{WIMP}) \cong 20$ GeV	$S_2/S_1 + F$	< 10 decays/t·s	10^{-48} cm ²
	Xe 146(100) tons double-phase	$S_2/S_1 + F$ 3740 avalanche Photodiodes	$M^{\min}(\text{WIMP}) \cong 6$ GeV	$S_2/S_1 + F$ $K = 10^3$		
INR of RAS (proposal) [23]	Ar+Ge(CH ₃) ₄ (0.15 ppm) or Ar+C ₂ H ₄ (2 ppm) 1000 tons double-phase	S_2/S_1 GEM	$E_{nr}^{\min} = 10$ keV	S_2/S_1 $K > 10^{10}$	10^3 decays/t·s	$\leq 10^{-48}$ cm ²

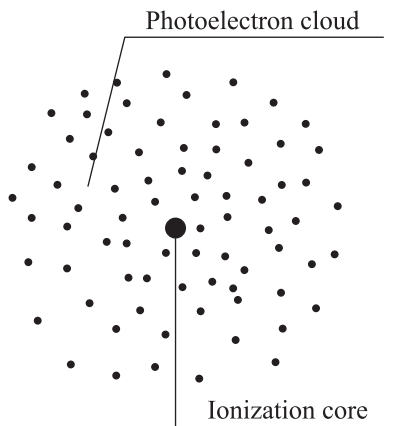


Fig. 1. The event structure

An alternative method for electron background suppression is a comparison of ionization S_2 and scintillation S_1 signals for every event. The ratio between

the ionization and scintillation signals in liquid Ar for $E = 100$ keV, at the electric field intensity of 1 kV/cm, is equal to [8]

$$S_2/S_1 = 150(e^-), 3(\alpha) \text{ and } 10(\text{nr}). \quad (3)$$

The additional charge in liquid Ar + 0.15 ppm TMG is produced mainly by photons, because the probability of the ionization at the Ar^{*}+TMG-collisions at this concentration of TMG is small [7].

The quantum efficiency of photo-ionization $h\nu(128 \text{ nm}) + \text{TMG} \rightarrow \text{TMG}^+ + e^-$ in a liquid Ar is equal to 50% [15].

The ionization core of a recoil ion or a background electron, at the concentration of TMG of 0.15 ppm, is surrounded by a photoelectron cloud of ~ 10 cm in diameter [14].

The measurement of the number of photoelectrons, surrounding the ionization core, ensures the high efficiency measurement of the scintillation signal amplitude,

the efficiency of which must be better than in a case of using of photomultipliers, and this should make it possible to obtain high suppression of the background.

The dependence $S_2/S_1 = f(E_{nr})$ is shown in Fig. 5 of work [8]. The quantity S_2/S_1 obtained by extrapolation, is equal to 40 for $E_{nr} = 10$ keV. The number of photons for $E_{nr} = 30$ keV is equal to 300 [8]. The ratio S_2/S_1 for electron background is changed little in the working range.

At present several experimental installations with high mass of liquid Ar and Xe for Dark Matter search have been proposed and developed, the main parameters of which are given in Table.

2. Experimental setup. As an example, the design of a chamber with a mass of liquid Ar of 20 tons is shown in Fig. 2. The ionization electrons and pho-

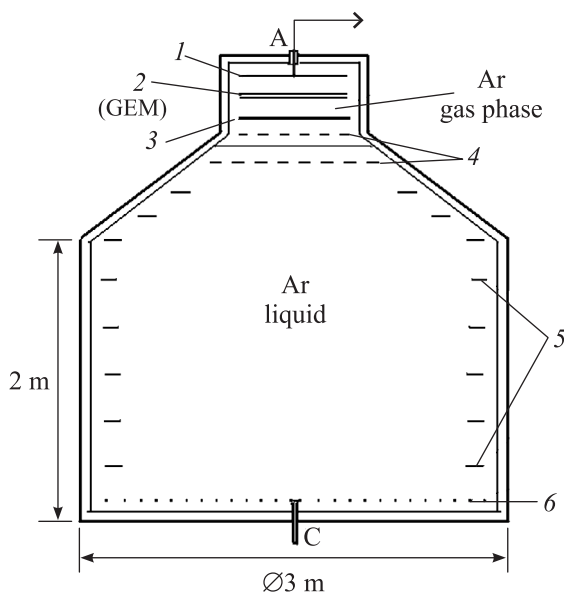


Fig. 2. Double-phase Ar chamber: 1 – anode, 2 – GEM detectors, 3 – light screen, 4 – grids for electrons transport from liquid Ar to gas phase, 5 – the ring electrodes for electric field level, 6 – cathode

toelectrons are detected with GEM of high reliability and stability [10–13]. The diameter of GEM is equal to ~ 70 cm.

The high three-dimensional spatial resolution of GEM ensures the detection of the ionization core and photoelectrons with high efficiency.

The light screen [24] is placed between the liquid Ar and the GEM detector to block the transmission of photons from the GEM to the volume of liquid Ar. On the other hand, this screen is transparent for electrons, which are passing through it from the liquid Ar to GEM with almost 100% efficiency. To suppress the secondary

scintillation from electrons moving in the gas phase of Ar in the region below the light screen, the hydrogen under a partial pressure of about 0.1 bar must be added to Ar gas phase. The cross section of the energy transfer in the reaction $\text{Ar}_2^* + \text{H}_2 \rightarrow 2\text{Ar} + \text{H}_2^*$ is equal to 4.2 \AA^2 . Therefore, the secondary scintillation must be fully suppressed [25].

The events, which take place near the cathode and the surface of liquid Ar can be picked out by analysis of the shape of photoelectron clouds. In addition these events will be removed due to high coefficient of the background suppression.

To reduce the background produced by the cathode, it must be wound with a carbon wire of $\varnothing 1$ mm at 50 mm pitch.

To suppress the background, the 5 cm thick layer of copper can be placed within the chamber.

The ring electrodes for the electric field forming must be produced from mylar covered with copper layer of about $5 \mu\text{m}$ thickness.

The neon under a partial pressure of ~ 1 bar [10–13] must be contained in the gas phase under the liquid Ar to decrease the difference of the potential between the GEM electrodes.

The addition of about 100 ppm Xe(N₂) in liquid Ar allows to suppress the triplet component of scintillation signals practically completely [7]. The singlet component is changed little for this addition. The relationships (3) in this case give the next numbers:

$$S_2/S_1 = 645(e^-), 5.31(\alpha), \text{ and } 13.3(nr). \quad (4)$$

The relationship $(S_2/S_1)_e/(S_2/S_1)_{nr} = 48.5$ allows to suppress the electron background completely [26].

The TMG and Xe additions do not influence each other.

The neutron background must be essentially suppressed due to multiple elastic and inelastic scattering of neutrons at Ar atoms in the course of their slowing [1]. The high 3D spatial resolution of the chamber allows to restore the picture of neutron scattering and to suppress this background too.

Since the decay rate of Ar^{39} in 20 tons of natural argon is about $2 \cdot 10^4 \text{ s}^{-1}$, for the total collection time of electrons from the volume of the detector of 2 ms, only about 40 background events can take place in the volume of the 20 tons chamber during that time, which gives 1 event per 500 kg of Ar. Therefore, the probability of overlapping of two such events is small and the Ar^{39} background can be completely suppressed. In a similar way the Ar^{39} background can be suppressed for even larger detection chambers, with volume of 1000 tons, for example.

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