Two-phase emission detectors in search for rare events with low energy depositions

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Abstract. This paper reviews applications of two-phase emission detectors using xenon as working media. This kind of detectors invented at MEPhI is extremely sensitive to ionization (down to single electrons) and can be very massive (in ton scale) in order to provide high count rate for quite rare events and organize an active shielding from natural radioactivity in the wall-les configuration of readout system. The emission detectors found their unique application in the most sensitive at the moment experiments searching for cold dark matter in the form of weakly interacting massive particles (WIMPs). The RED-100 detector recently constructed at NRNU MEPhI can be used for the first observation of the elastic coherent neutrino scattering off xenon nuclei when the detector is installed practically on the Earth's surface.

1. Introduction

The emission method of particle detection allows the detection of individual ionization electrons in massive detector media [1]. Using two-phase emission detector based on condensed noble gases in "wall-less" configuration, 3D digital selection of point-like events can be provided in fiducial volume of the detector medium as shown in figure 1. Ionizing particles interacting with the condensed noble gas generates a fast scintillation signal *Sc* serving as a trigger and a number of ionization electrons that due to applied electric field drift to the interphase surface and at high enough electric field strength escape into the rarefied gas (or superconductive collector, for cryogenic crystal targets [2]) where generate a second, amplified signal *EL*. An array of sensors can be used to measure the two-dimensional distribution of the secondary particles and to determine the coordinates of the original event on the plane of the sensor array. Since the second signal is delayed from the first one, the third coordinate of the original point-like interaction is also uniquely determined in the time-projection mode. From the three-dimensional position reconstruction, a fiducial volume *A* is defined. Then, events originating out of the volume *A* in the vicinity of the detector walls can be eliminated as being potentially associated with radioactive background radiated from the surrounding materials. By making the detector sufficiently large and choosing a target medium with a high stopping power for natural radiation (like xenon), the fiducial volume is effectively shielded by the outer detector medium layer *B*. The layer *B* can be used as active shielding to reject events in the fiducial volume *A* correlated with detected interactions in the layer *B* and an outside active shielding if needed (not shown in figure 1). That allows rejection of events associated with multiple scattering background particles such as neutrons. Analysis of redistribution of energy deposited by detected particles between ionization (*EL* signal in figure 1), photon- or/and phonon excitations (*Sc* signal in figure 1) improves the efficiency of background suppression. All listed features, along with the availability of super-pure noble gases in large amounts, make condensed noble gases the most attractive media for detectors of rare events with low energy depositions.

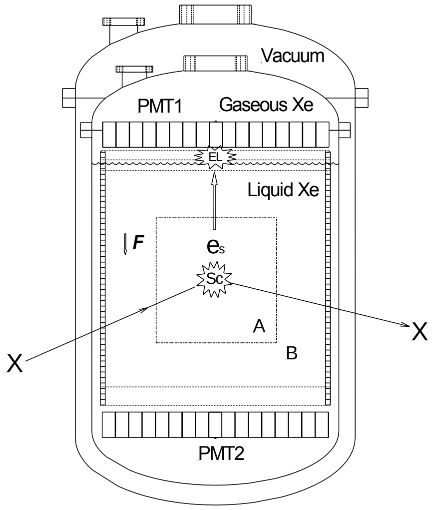

Figure 1. Principal of operation for a liquid xenon "wall-less" two-phase emission detector detecting hypothetic weakly interacting particle *X*: *Sc* – scintillation flash generated at the point of primary interaction between X and Xe atoms; *EL* – electroluminescence flash of gaseous Xe excited by electrons extracted from liquid Xe by electric field *F* and drifting through the gas at high electric fields (>1 kV/cm/bar); *PMT1* and *PMT2* – arrays of photodetectors detecting *Sc* and *EL* signals; *A* – the fiducial volume where events considered to be useful occurred; *B* – the shielding layer of LXe. The active volume of the detector is surrounded with highly reflective cylindrical Teflon reflector embodied with drift electrode structure providing uniform field *F*.

2. Search for WIMPs

The most fundamental problem of modern astrophysics is the missing mass of the universe, which indicates its presence only via gravitational forces. According to the standard model of cosmology, the total mass–energy of the known universe contains 4.9% ordinary baryon matter, 26.8% dark (invisible) matter and 68.3% dark energy [3]. Thus, dark matter constitutes 84.5% of the total matter in the universe with a local density of about 0.3 (GeV/c^2)/cm^3 [4]. However, the nature of dark matter remains unknown, providing a central problem for cosmology for more than two decades. One possible explanation of the invisible mass is that it consists of nonbaryonic *weakly interacting massive particles* (WIMPs) expected in the super symmetry model (SUSY). The model predicts that masses of such particles are scaled in the range from 10 to 10^4 GeV/c^2 and that they can interact with baryonic matter via the weak nuclear force and gravity, or possibly other interactions with cross-sections no higher than the weak scale [5].

The most popular approach for observing WIMPs is to search for direct WIMP-nucleus scattering. This approach requires to look for energy depositions in the sub-keV energy range in targets with mass of at least hundreds kilograms and provides an efficient rejection of background from natural radioactivity and cosmic rays. The two-phase emission detector technology can satisfy the challenging requirements of the advanced instrumentation to observe extremely rare interactions of very weakly ionizing astroparticles.

A number of successful experiments arranged by ZEPLIN, XENON, LUX and PandaX collaborations with LXe emission detectors during 10 years period reduced allowed region of existence for WIMPs with mass of 40-50 GeV/c^2 from $8.8{\cdot}10^{-44}$cm^2 (reported by XENON-10 collaboration in 2006) down to $1.1{\cdot}10^{-46}$cm^2 (reported by LUX collaboration at the end of 2016) as shown in table 1.

Detector LZ of the second generation (G2) installed at Davis' cage of the Homestake mine by joint collaboration of former LUX and ZEPLIN experiments will use 6 ton LXe active mass emission detector and can reach sensitivity below 10^{-47} cm^2 for spin-independent interactions. With the increasing detector mass and sensitivity, solar neutrino interactions become an irreducible source of background for WIMP search experiments. Multi-ton active mass WIMP detectors of the upcoming G3 generation shall become, even with naturally occurring isotope abundances, sensitive to double-beta decay at the modern level of sensitivity and solar neutrinos interactions via elastic coherent scattering off xenon nuclei. Detectors of G3 generation such as DARWIN can achieve spin-independent cross sections for WIMPs as low as $\sim 10^{-49}$cm^2 with masses above 5 GeV/c^2 [18] and will be capable for multi-task experiments of high interest.

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Table 1. Direct dark matter search experiments with two-phase LXe emission detectors providing the best limits for WIMP existence

Project	Detector mass, Total/Fiducial, LXe kg	Achieved sensitivity, 10^{-44}cm^2 @ GeV/c^2	Location, Years on duty	Status	Ref.
XENON-10	25/5	8.8 @ 100; 5.5 @ 30	GS, 2006-07	Completed	[6,7]
ZEPLIN II	31/8	66 @ 55	BM, 2006-07	Completed	[8]
ZEPLIN III	12	2.9 @ 50	BM, 2008-2009	Completed	[9]
XENON-100	170/62	0.11 @ 50	GS, 2008-2014	Completed	[10]
LUX	360/250	0.011 @ 50	H, 2013-2016	Completed	[11]
PandaX-II	500/300	0.025 @ 40	J, 2015-now	Active	[12]
XENON1T	2200/1100	~0.001 @ 40	GS, 2016-now	Active	[13]
LZ	7000/6000	~0.0001 @ 50	H, 2018-2025	u/c	[14]
DARWIN	40000/30000	~0.00001 @ >5	GS, 2023-2030	Project	[18]

Notes: (BM) Boulby mine (England); (GS) Gran Sasso Underground Laboratory (Italy); (H) Homestake DUSEL (USA); (J) JinPing (China); (u/c) under construction.

3. Observation of coherent neutrino scattering

According to the Standard Model the process of neutrino elastic interaction with a massive nucleus via coherent scattering has relatively large cross section:

$$\sigma \approx 0.4\cdot 10^{-44} N^2 (E_\nu)^2 \,\mathrm{cm}^2,$$

where N is the neutron number and the neutrino energy E_ν is measured in MeV [15]. The formula is valid for neutrino energies up to about 50 MeV, and thus can be applied to reactor, solar and supernova generated neutrinos. The magnification factor N^2 gives a significant increase in cross section for detectors using heavy nuclei as target. This fact can pave a way using relatively compact neutrino detectors based on LXe for nuclear reactor monitoring. The coherent neutrino scattering has never been observed experimentally because of the very low (<1 keV for nuclear reactor electron antineutrino) kinetic energy of recoil nucleus.

The RED-100 two-phase emission detector using 200 kg liquid Xenon as a working medium recently has been constructed at NRNU MEPhI and can be used for the first observation of the neutrino coherent scattering effect in 2018-2019 at the Kalinin NPP providing ~10^{13} cm^{-2}s^{-1} electron antineutrino flux at testing facility shielded from hadron component of cosmic rays and in 5 times reduced cosmic muon flux [16].

4. Conclusion

Today, the emission detector technology has become the basis for the second generation of the cold dark matter experiments searching for WIMPs with up to 10 tons targets and already considered for the third generation of the cold dark matter experiments with up to 40 tons LXe working media. This kind of emission detectors are also being considered for the detection of rare events such as neutrino coherent scattering off heavy nuclei and had been proposed for observation of positron double-beta decay [17]. All these exciting opportunities can be achieved due to unique combination of detection properties of emission detectors such as

- extremely effective suppression of the natural radioactive background due to three-dimensional imaging capability with electronic readout and effective self-shielding;
- availability in huge masses (tens or even hundreds tonnes) in order to provide a reasonable counting rate for events with extremely low cross-sections;
- effective rejection of background and identification of particles due to multi-mode readout in excitation and ionization channels of energy depositions;
- possibility to use isotopically enriched targets.

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