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Experiments on direct dark matter search with two-phase emission detectors

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Abstract

Emission detectors, invented 45 years ago in MEPhI, found their unique application in modern experiments searching for cold dark matter in the form of weakly ionizing massive particles (WIMPs). The current best limits for the interaction cross sections of supersymmetric WIMPs having a mass of 100 GeV/c^2 with nucleons were measured with emission detector LUX containing 360 kg of liquid xenon as detector medium installed in Davis' cave at Homestake mine in South Dakota. Emission detectors of the next generation G2, with an active detector mass of about 10 tons, will either unambiguously detect WIMPs or rule out all current theoretical predictions for WIMP existence. Detectors of the G3 generation will be used for multiple purposes including detection of double beta neutrinoless decay and low-energy neutrinos

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Keywords: emission detector; dark matter; WIMP; liquid xenon; neutrino; double beta-decay.

1. Introduction

The most fundamental problem of modern astrophysics is the missing mass of the universe, which indicates its presence only via gravitational forces. According the standard model of cosmology, the total mass–energy of the known universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy [1]. 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 Read [2]. However, the nature of dark matter remains unknown, providing a central problem for cosmology for more than two

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decades. One possible explanation of the invisible mass is that it consists of non-baryonic *weakly interacting massive particles* (WIMPs) expected in the Supersymmetry model. 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 [3]. One popular approach for observing WIMPs is to search for direct WIMP-nucleus scattering. A problem is that this approach requires a search 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. In this paper, we review the two-phase emission detector technology that can satisfy the challenging requirements of the advanced instrumentation to observe extremely rare interactions of very weakly ionizing astroparticles.

2. Emission method of particle detection

The emission method of particle detection was invented 45 years ago at MEPhI's department of experimental nuclear physics [4]. In a several years of development tracking emission detectors it was recognized that the method can be used for detection of weakly ionizing particles in massive condensed dielectrics [5]. A band diagram of a diode emission detector is shown in Fig. 1. Quasi-free electrons generated by a detected particle X lose their original energy by generating secondary ionizations and excitations in the condensed medium (at relaxation length χ), drift to the interface surface, penetrate the surface potential barrier Δ and escape into the rarefied phase (gas or vacuum). In a vacuum, electrons can be accelerated by the electric field F_2 before reaching the anode. The energy acquired from the electric field $E3$ can result in secondary ionizations at the anode and thus amplify the electron signal. In a gas, drifting electrons can acquire energy E_2 that can be sufficient to excite the gas and generate electroluminescence or result in avalanche multiplication of the electrons. Both processes can be used to amplify the electron signal. Additional $E2+\varphi^a$ energy gain is possible if superconductive anodes connected to transition-edge sensors (TES) are used to collect ionization electrons as shown in [6].

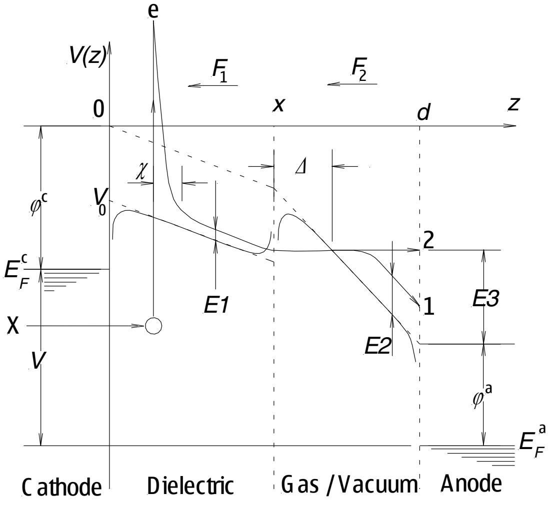

Fig. 1. Band diagram of diode emission ionization chamber with non-polar dielectrics working medium of thickness x and between-electrode gap d biased with voltage V detecting X ionizing particle.

The first attempt to image tracks of anomalous low-ionizing particles generated in high energy particles interactions was undertaken using a streamer emission chamber constructed at MEPhI and exposed to the beam of 3.7 GeV/c pions at the ITEP proton synchrotron [7]. In 1989 an idea was published to use an emission detector based on 100 liters of room temperature liquid isooctane to search for 1-10 GeV/c^2 WIMPs [8]. However, the best performance for WIMP detection was likely through the use of "wall-less" emission detector with 3D digital selection of point-like interactions in fiducial volume proposed by Bolozdynya et al. in 1995 [9] as shown in Fig. 2:

1. Radiation interacts with the condensed target medium, exciting and ionizing atoms; this process generates a prompt signal that manifests itself in the form of scintillation in noble liquids and solids, phonons in crystals, and rotons in superfluid helium. This signal serves as a trigger.
2. Under influence of the applied electric field ionization electrons drift to the surface of the condensed medium and then escape into the rarefied gas or vacuum region (or superconductive collector, for cryogenic crystal targets) where generate a second, amplified signal. An array of sensors is 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 interaction is also uniquely determined in the time-projection mode.
3. From the three-dimensional position reconstruction, a fiducial volume *A* can be defined. Then, events originating in the vicinity to 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 nuclear radiation, 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 Fig. 2). That allows rejection of events associated with multiple scattering background particles, for example, neutrons.
4. Analysis of redistribution of energy deposited by detected particles between ionization (*EL* signal in Fig. 2), photon- and phonon excitations (*Sc* signal in Fig. 2) improves the efficiency of background suppression.

The above listed features, along with the availability of super-pure noble gases in large amounts, make condensed noble gases the most attractive media for emission detectors of rare events. It is important to point out that there are other detector technologies that can be used to construct “wall-less” detectors. For example, bulk scintillators viewed by a photo-detector array totally surrounding the “crystal-ball” have been considered as ‘wall-less’ detectors for such experiments as XMASS, CLEAN. However, emission detectors based on pure noble gases require fewer readout channels and allow identification of interactions since the first signal is proportional to the excitation of the condensed medium; the second is proportional to the ionization.

The first really wall-less emission detector was constructed by XENON collaboration in 2005-2006 [10]. The detector XENON-10 contained 13.5 kg of liquid xenon (LXe) in a 15 cm diameter and 15 cm deep sensitive volume. Due to the relatively small size of XENON-10, the background reduction due to active self-shielding was quite modest. The most background was suppressed by passive gamma and neutron shielding. The passive shield has 30 cm of polyethylene (2.2 tons), and 23 cm of Pb (27 tons). The electron-recoil (ER) background in an inner fiducial volume (FV) of 5.4 kg LXe was ~ 0.6 evt/keVee/kg/day* for single scatter events with valid S1 (prompt light) and S2 (proportional light) signals. XENON-10 clearly demonstrated that, by selecting an inner FV, one can effectively eliminate events with partial charge collection when it occurs near the edge of the LXe active volume. After cuts were applied to remove anomalous events, the energy window of interest was analyzed for the 58.6 live-days of WIMP-search data at the Gran Sasso Underground Lab. At the 90% CL, the upper limit for the WIMP-nucleon cross-section was determined to be $8.8\cdot10^{-44}$ cm^2 at a WIMP mass of 100 GeV and $4.5\cdot10^{-44}$ cm^2 at 30 GeV.

New results for spin-dependent WIMP-nucleon interactions with ^{129}Xe and ^{131}Xe were reported in 2008 [11] after 58.6 live days of operation. Based on the non-observation of a WIMP signal in a fiducial volume containing 5.4 kg of liquid xenon, previously unexplored regions in the theoretically allowed parameter space for neutralinos were excluded. Also excluded was a heavy Majorana neutrino with a mass in the range of ~ 10 GeV/c^2–2 TeV/c^2 as a dark matter candidate under standard assumptions for its density and distribution in the galactic halo. In 2007, the best limits for WIMP–nucleon cross-sections were reported from a 136 kg·d exposure of the XENON-10 LXe emission detector.

At the beginning of 2009, the best limit for the spin-dependent WIMP–nucleon cross-sections was reported from the first run of the ZEPLIN-IIILXe emission detector by Lebedenko et al. [12].

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[*] The unit keVee is used for electron recoil equivalent energy; keVr is used for nuclear recoil equivalent energy.

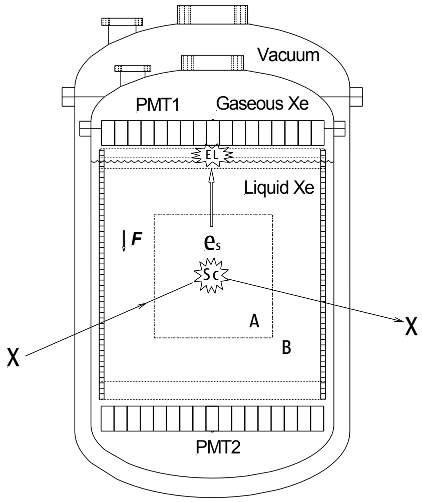

Fig. 2. Principal of operation for a liquid xenon "wall-less" emission detector detecting hypothetic weakly interacting particle *X*: *Sc*– scintillation flash generated at the point of primary interaction between X and Xe atoms; *EL* – electroluminescence flash of gaseous Xe excited by electrons extracted 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*.

Much greater sensitivity has been achieved with XENON-100 detector, currently running at Gran Sasso. This member of the XENON detector family contains 170 kg of xenon with 65 kg in the FV and 105 kg in the active shield. With a 6000 kg·d exposure, the experiment is expected to reach a sensitivity for spin-independent WIMP-nucleon interactions down to $2 \cdot 10^{-45}$ cm^2 cross-section at a WIMP mass of 100 GeV/c^2 by the end of 2009 [13]; and the upgraded XENON-100, with a low-background copper vessel, better krypton separation, and improved passive and adding active shielding has improved this sensitivity by an order of magnitude [18].

The Large Underground Xenon (LUX) collaboration is running a 360 kg active mass, two-phase LXe emission detector for a deep underground experiment provided the best current limit with an event rate better than ~ 1 event/100 kg/month that corresponds to a spin-independent WIMP-nucleon cross-section of $7.6 \cdot 10^{-46}$ cm^2 at a WIMP mass 33 GeV/c^2 [14]. Detector LZ of the second generation (G2) will be constructed at the same Davis' cage of the Homestake mine by joint collaboration of former LUX and ZEPLIN experiments. The LZ detector will use 8 ton LXe active mass and can reach sensitivity below 10^{-47} cm^2 for spin-independent cross-sections. The sensitivity of some direct WIMP search experiments using two-phase emission detectors in the last decade are compared in Table 1.

With the increasing detector mass and sensitivity of dark matter experiments, neutrino interactions will soon become an irreducible source of background for WIMP search experiments, at which point neutrinos can be considered as special objects of interest. Multi-ton active mass WIMP detectors of the next G3 generation shall become, even with naturally occurring isotope abundances, sensitive to double-beta decay and solar neutrinos, making them useful for multi-task experiments. A possibility to use isotope enriched targets for axion detection is still open as shown in [15].

Table 1. Direct dark matter search with two-phase emission detectors

Project	Detector mass, Total/Feducial, kg	Achieved sensitivity, $10^{-44}cm^2$ @ GeV/c^2	Location, years on duty	Status	References
XENON-10	25/5 LXe	8.8 @ 100; 5.5 @ 30	GS, 2006-07	Completed	[11]
ZEPLIN II	31/8 LXe	66 @ 55	BM, 2006-07	Completed	[12]
XENON-100	170/105 LXe	0.2 @ 100	GS, 2008-now	Active	[13]
LUX	360/100 LXe	0.07 @ 100	H, 2013-now	Active	[14]
DarkSide-50	46 LAr	6.1 @ 100	GS, 2013-2014	Completed	[16]
PandaX-I	37 LXe	3.7 @ 49	J, 2014	Completed	[17]
PandaX-II	500/300 LXe		J, 2015	u/c	
XENON1T	2200/1100LXe		GS, 2016	u/c	[18]
LZ	7000/6000 LXe		H, 2018	u/c	[19]

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

3. Conclusion

At the beginning of the 21st century, highly sensitive two-phase emission detectors are leading technology to drive down the limits for cold dark matter scattering cross-sections. 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. Emission detectors are also being considered for the detection of rare events such as neutrino coherent scattering off heavy nuclei [20] and proposed to detect positron neutrinoless double-beta decays[21]. All these exciting opportunities look achievable, especially because of 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;
- rejection of background and identification of particles due to multi-mode readout in excitation and ionization channels of energy depositions;
- possibility to use massive isotopically enriched targets.

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