

# Development of Two-Phase Emission Detectors in Russia

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**Abstract:** This paper reviews the history of the development of two-phase emission detector technology that was invented 50 years ago at the Moscow Engineering Physics Institute and is currently being used to search for dark matter, novel neutrino physics and double beta-decay in several internationally running experiments.

**Keywords:** two-phase; emission; detector; technology; dark matter; neutrino

## 1. Introduction

The emission method for the registration of elementary particles is the brainchild of the development in the USSR of track detectors for high-energy physics. With the rapid development of high-energy physics in the 1950s–1960s, it became necessary to develop a controlled (in comparison with bubble chambers) technology for recording high-energy particle tracks. Improvements in spark chamber technology have led to the creation of a streamer chamber in which a spark discharge caused by ionization electrons under the influence of a nanosecond high-voltage pulse is interrupted at the streamer stage of its development. In the simplest case, to organize streamers, a high-voltage pulse with a duration of about 10 ns is applied to the electrodes of a plane-parallel ionization chamber filled with a noble gas, so that the spark discharge, as soon as it starts in several places along the particle track, is interrupted. Electronic avalanches interrupted barely starting to develop, form a chain of short sparks that is referred to as a streamer. During the development of the discharge, the front of the streamer moves at a speed of up to  $4 \times 10^6$  m/s in fields of  $\sim 30$  kV/cm; therefore, very short voltage pulses are required for the streamer’s length to be several millimeters. Streamers are formed in the direction of the electric field, starting from the initial ionization electrons along the track of the ionizing particle. The streamer chain is photographed, and after processing the film, it allows you to determine the track, i.e., coordinates of the path of movement of the ionizing particle in the medium.

The first working streamer chambers were developed in the USSR in 1963 by G.E. Chikovani with colleagues from the Institute of Physics of the Academy of Sciences of the Georgian SSR and independently B.A. Dolgoshein with colleagues from the Moscow Engineering Physics Institute. In terms of contrast and image resolution, streamer chambers are inferior to bubble chambers, but controllability with an external trigger allows them to be used for studying processes with a low probability. He, H<sub>2</sub>, mixtures of Ne + He, He + CH<sub>4</sub>, and D<sub>2</sub> + CH<sub>4</sub> at a pressure of  $p = 1$  bar are usually used as a working gas in streamer chambers. The coordinate resolution of the streamer chamber is determined by the dimensions of the streamers, which, as a rule, have a diameter of  $\sim 1$  mm and a length of  $\sim 5$  mm, with a density along the track of  $\sim 10$ – $12$  cm<sup>-1</sup>.

In 1968, Boris Anatolyevich Dolgoshein and his team built a record-size streamer chamber with a volume of  $8 \times 2 \times 1$  m<sup>3</sup> at MEPHI to search for W bosons. The camera worked for many years at the U-70 proton synchrotron in Protvino. With the help of this camera, fast muons were identified for the first time; their spectrum and polarization were



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measured. Unfortunately,  $W$ -bosons were not discovered by this remarkable device for the reason that the energy of U-70 (a record at the time when this machine was launched in 1967) was not enough to form particles, the mass of which turned out to be about  $80 \text{ GeV}/c^2$ . The  $W$  boson was discovered in 1983 at CERN, for which Carlo Rubbia and Simon van der Meer were awarded the Nobel Prize in physics in 1984, a record short time after the discovery.

The successful development of streamer technology for visualizing the tracks of relativistic particles in pure noble gases was awarded the Lenin Prize in 1970 with the formulation “for creating a new type of track detector capable of detecting complex events in the interaction” of elementary particles. An attempt to create a chamber with an adjustable guide with a medium denser than gas at room temperature and a pressure of 1 bar prompted the authors from MEPhI to try to increase the density either by lowering the temperature of the working medium for the gas or by using liquefied noble gases instead of gas. In the first area, experiments were carried out at ITEP in the laboratory of V.A. Lyubimov, where I.V. Sidorov built a cryogenic streamer chamber filled with helium, a neon–helium mixture (70% Ne + 30% He) or hydrogen and operating at a temperature of 80–100 K [1]. In these experiments, a surprising phenomenon was discovered: the visualization voltage (the threshold for the development of streamers) practically did not change with decreasing temperature and increasing the density of the gaseous medium, and streamer tracks became more compact, dense and bright. However, the cryogenic streamer chamber turned out to be a rather cumbersome device, which is difficult to fit into the configuration of modern accelerator experiments with the geometry of detecting installations close to  $4\pi$ , and, therefore, this work was not further developed.

At about the same time, B.A. Dolgoshein and his colleagues at MEPhI studied liquid argon as a possible working medium for a streamer chamber with a dense working medium. They failed to provide a streamer discharge in liquid argon, but they showed that electrons arising as a result of ionization of liquid argon by high-energy particles can be extracted from a liquid by a rather moderate ( $\sim 1 \text{ kV/cm}$ ) electric field into an equilibrium gas phase, where they can be register by using spark technology [2].

## 2. TPED Technology Development

### 2.1. Two-Phase Emission Spark Chamber

The first operating two-phase emission detector (TPED) was a liquid argon spark emission chamber [3]. It was a two-electrode plane-parallel ionization chamber with a gap between the electrodes of 1.6 cm. A disk alpha source that was 3.5 cm in diameter was installed in the center of the disk-shaped cathode immersed in liquid argon. An anode was performed as a flat grid made of parallel Nichrome wires of 0.2 mm diameter placed with a step of 0.6 mm. The anode was located in the equilibrium gas phase above a 1.4 cm–thick layer of liquid argon, covering the cathode, which served as the bottom of the chamber. The gas phase consisted of a 50% Ar + 50% Ne mixture. The ionization electrons extracted by the  $3 \text{ kV/cm}$  electric field from alpha-particle tracks in liquid were collected at the anode. Voltage pulses generated by high-voltage Arkadiev–Marx generator with 40 kV amplitude and 100 ns duration were applied to the anode. If some ionization electrons were located near the anode at the moment the pulse was applied, a spark discharge appeared at this place. An optically transparent window was installed above the anode and was used for picturing the sparks. The image of the two-dimensional distribution of the activity of the alpha source was formed as a superposition of images of many spark discharges near the anode wires.

This technology has not found real practical application, but it has shown that it is technically possible to construct an emission streamer chamber.

### 2.2. Two-Phase Emission Streamer Chamber

To implement the idea of two-phase emission streamer chamber, B.U. Rodionov and his students built a special detector at MEPhI. A hard krypton disk 12.5 cm in diameter and

5 mm thick, at a temperature of 78 K, was used as a working medium in this detector, and a 1 cm-wide gas gap between the free surface of the disk and the mesh anode was filled with neon at a pressure of 1 bar. Tracks of relativistic particles drawn by a constant electric field of 1.5 kV/cm strength from solid krypton were recorded in the gas phase in the form of a chain of streamers. Particles passing through solid krypton were separated from the beam of relativistic particles, using a telescope of external scintillation counters. The counters generated a trigger signal that triggered the Arkadyev–Marx high-voltage pulse generator to supply a high-voltage pulse with amplitude of 100 kV and duration of 60 ns to an anode suspended from an optical window above solid krypton.

In the late 1970s, in a special experiment on the secondary beam of the ITEP proton synchrotron, it was shown that the detector is indeed capable of visualizing the tracks of pions passing through solid krypton with pulses of 3 GeV/c in the form of a chain of streamers (each with a diameter of  $\sim 0.5$  mm and length of 2 mm). In this case, the density of streamers along the track was about  $1 \text{ mm}^{-1}$ , which provides a significantly improved spatial resolution compared to conventional gas streamer chambers [4].

The study of the properties of the emission streamer chamber confirmed the observation first made in the study of the properties of the cryogenic streamer gas chamber [1] that, despite the increased density of the cold working gas in comparison with the gas at room temperature, the threshold field strength for creating streamers in the emission streamer chamber remains unchanged at a level of about 2 kV/cm. It was suggested that this effect is associated with an increase in the concentration of noble dimeric molecules with decreasing temperature. Since the ionization potential of dimers is reduced by 1–2 eV in comparison with atoms, the average ionization potential of the medium decreases in proportion to the increase in the gas density, as a result of which the visualization field strength remains practically unchanged.

In the course of analyzing the results of the exposure of this camera on a beam of relativistic pions, anomalous tracks with a very low ionization density were found: one streamer per 1–2 cm of the track length. More detailed studies showed that this was a memory effect of a two-phase medium associated with the capture of a part of electrons at the interface: anomalous tracks were recorded in the exact same place where the track of a relativistic particle with a normal ionization density ( $\sim 2 \text{ MeV/g/cm}^2$ ) was situated. Based on the results of this experiment, the idea was formulated about the possibility of detecting particles with an abnormally low ionizing ability (up to one electron per several centimeters of the track length) by using such detectors [5].

In the 1980s, the Nadezhda emission streamer chamber (Figure 6.6, [6]) was built at ITEP. In this detector, a massive sample of liquid krypton had been used as a working medium located in a vessel of 50 cm in diameter and 20 cm height and a cryogenic streamer chamber with a diameter of 1.5 m has to be used for visualization of high energy particles traces. It was proposed to use this device to study the multiple generations of neutral pions during the annihilation of antiprotons in heavy nuclei. The ability to visualize tracks with a relatively high ionization density with this camera has been experimentally tested by using an ultraviolet laser. The possibility of operating this chamber in the emission mode with a record amount of the working substance for an emission detector at that time of 75 kg was also tested [7,8]. However, the fully assembled detector was not tested at that time, due to problems with funding scientific works in the USSR in the early 1990s.

In parallel with the study of the possibility of visualizing the tracks of high-energy particles in dense working media, electronic methods for detecting particles in condensed working media, using scintillation in the condensed phase and electroluminescence or gas amplification in the gas phase, began to be actively developed.

### 2.3. Ionization TPED

In ionization TPEDs, the interaction of ionizing particles with a condensed matter is recorded by analyzing the shape of the ionization signal taken from the electrode system. Such detectors were used in the early stages of the development of radiation detectors

when registering sufficiently intense ionization signals generated by alpha particles [9], electron accelerators [10] or X-ray tubes [11–13] in order to study the properties of electron emission of various condensed dielectrics, including saturated liquid hydrocarbons, such as hexane, isooctane and tetramethylsilane [14,15], considered for the possibility of creating two-phase emission detectors operating at room temperature.

Ionization TPEDs were widely used in the early stages of R&D for methodological studies of the emission properties of possible working media, including condensed heavy noble gases (argon, krypton and xenon) and saturated hydrocarbons (methane, hexane, isooctane, tetramethylpentane and tetramethylsilane).

#### 2.4. TPED Using Gas Gain Technology

The first TPEDs were created during a period of explosive development of multiwire proportional chamber (MWPC) technology invented by George Charpak et al. [16] to address the pressing challenges of high-energy physics. For this reason, in the first emission chambers, multi-wire anodes were most often used, which made it possible to study the possibility of gas amplification of ionization signals.

One of the first emission detectors of this type was a two-electrode liquid-argon ionization chamber that was similar in design to the detector used to visualize alpha-particle tracks (Figure 6.1, [6]). The electronic signal was recorded by using wire anodes with wire diameters in the range from 50 to 200  $\mu\text{m}$ . Initially, attempts were made to obtain gas amplification at the wire anode in an equilibrium gas phase, but, in this mode, it was impossible to obtain stable gas amplification with a coefficient of more than 500. To create conditions for more stable gas amplification, the wire anode was immersed in liquid argon, and the anode wires were heated with an electric current of 0.1–1 A in order to create a gas envelope around them and limit the development of an avalanche to the size of bubbles formed by liquid boiling on the wires. In this mode, it was possible to register electrons with a gain of up to  $10^4$ . However, in this case, the dead time increased to 10 ms compared to 0.1 ms in a gas, which was probably due to the localization of a significant amount of positive ions inside the bubbles. When using a pulsed high voltage, the gas gain could be increased to  $10^6$  [17]. However, this technique did not find practical application, since it required huge energy consumption for heating the anode wires and boiling liquid argon around them.

Attempts to organize gas amplification at wire anodes located in an equilibrium gaseous medium above liquid saturated hydrocarbons have proved more successful. In particular, the emission of electrons from liquid isooctane at room temperature could be observed by using a wire anode placed in the gas phase with a gas amplification of  $3 \times 10^4$  [18], and from liquid 2,2,4,4-tetramethylpentane—with a gas gain of  $\sim 10^3$  [19].

Attempts to use organic impurities in liquid noble gases to organize gas amplification in an equilibrium gas phase were unsuccessful, since this inevitably led to cooling of electrons drifting to the interface and, accordingly, reduced the probability of electron emission into the gas phase.

A new phase in the development of gas amplification technology for TPED was initiated by the invention of gas electron multipliers (GEMs) by Fabio Sauli in 1997 [20]. It turned out that this technology is quite compatible with argon as a TPED working substance, and when using structures with triple GEM, the amplification of the electron signal can reach 5000. Unfortunately, in xenon TPEDs, this technology did not allow for the obtainment of gas amplification of more than 200 [21].

The next step in the development of technology for amplifying gas signals in two-phase emission liquid-argon detectors was the creation of mechanically strong “thick” (ThGEM) [22,23] and “large” (LEM) [24] that can be used to amplify signals (with a factor of 10–20) in TPED based on liquid argon, for example, to study high-energy neutrino oscillations on long bases [25]. ThGEM can also be used to read TPED signals in liquid argon in combination with SiPM matrices [26,27].

### 2.5. Electroluminescence TPED

The development of electroluminescent TPED technology began with the creation of miniature detectors with a working medium volume of  $\sim 1 \text{ cm}^3$  to study the scintillation and emission properties of condensed argon, krypton, xenon, methane and their mixtures [18,28,29]. A qualitatively new stage in the development of emission detector technology was the development of a position-sensitive electroluminescent gamma camera with a hexagonal matrix made of photomultipliers [30] that was proposed to be used to visualize gamma-radiation fields in nuclear medicine.

The development of this technology has led to the idea of recording two signals from one event: a scintillation signal (it is often called the S1 signal) which occurs at the moment of interaction of the registered particle with the condensed working medium of the detector, and the subsequent electroluminescence signal (S2), which arises as a result of the electroluminescence of a gas medium during drift of emitted electrons through it in an electric field of sufficiently high strength. Using these two signals to record quasi-point events allows the position of the interaction point in three-dimensional space to be determined to create a “wall-less” detector for recording rare events, such as interactions with neutrino-baryonic matter and exotic particles which can make up the dark matter of the Universe [31]. This possibility of reconstructing a three-dimensional picture of the interaction of particles in a dense noble gas was first demonstrated while using compressed xenon [32], and it was proposed to use two-phase electroluminescent emission chambers of this type to search for rare processes with weak ionization signals, including cold dark matter and neutrinos [33].

## 3. Dark Matter Search Experiments

Over the past 10 years, the world’s best results on limiting the existence of massive particles of a cold dark matter (WIMPs) have been obtained by using TPED detectors, and the mass of the working substance of the used TPED detectors reaches several tons (most often liquid xenon) [34,35]. It is assumed that the next generation of dark-matter detectors will use liquid xenon weighing 50 tons or more as a working medium [36]. Russian physicists from NRNU MEPhI, NRC Kurchatov Institute, Moscow State University, Novosibirsk Institute, named after Budker, take an active part in setting up such experiments (Table 1).

A number of successful experiments of the first generation (G1) arranged by ZEPLIN, XENON and LUX collaborations with LXe emission detectors during a 10-year period lowered the area of the existence of particles with a mass of  $40\text{--}50 \text{ GeV}/c^2$  from level below  $8.8 \cdot 10^{-44} \text{ cm}^2$  (reported by XENON10 collaboration in 2006 [37]) to below  $2 \cdot 10^{-45} \text{ cm}^2$  (reported by XENON100 collaboration in 2014 [38]) and then below  $1.1 \cdot 10^{-46} \text{ cm}^2$  (reported by LUX collaboration at the end of 2016 [39]).

TPED of the second-generation (G2) LZ with 7 ton LXe active mass is currently installed at Davis’ cage of the Homestake mine by joint collaboration of former LUX and ZEPLIN experiments in order to reach sensitivity about  $10^{-47} \text{ cm}^2$  for spin-independent WIMP-nucleon interactions. TPED of G2 XENON1T/nT can achieve spin-independent cross-sections for WIMPs as low as  $1.4 \cdot 10^{-48} \text{ cm}^2$  for WIMPs of  $50 \text{ GeV}/c^2$  mass [34,40].

TPED of G3 generation DarkSide with 50 tons of liquid argon in active volume can achieve spin-independent cross-sections for WIMPs as low as  $\sim 7.4 \cdot 10^{-48} \text{ cm}^2$  for WIMPs of  $1 \text{ TeV}/c^2$  mass [39]. Multi-ton active mass LXe WIMP detectors of the third generation, such as DARWIN [36], shall become quite sensitive to observing double-beta decays of naturally abounded isotopes.

Searching for neutrino-less transitions in positron decays gives a unique signature because of the possibility to select these extremely rare events in coincidence with annihilation photons. TPED can be used to search for positron double-beta decays of  $^{124}\text{Xe}$  and  $^{78}\text{Kr}$ , using the 3D position-sensitive emission detector of  $\sim 1 \text{ m}^3$  total volume filled with liquid xenon, liquid krypton or their mixture and optionally surrounded with scintillators [33]. The emission detector can be triggered by scintillations that occur in the liquid at the moment that the decays happened. A unique feature of the proposed experiment is the very

specific topology of the useful events that makes the experiment comparable in sensitivity with tracking experiments. In case  $2\beta^+$ -decay, the useful event will contain 5 point-like ionization clusters (vertices) cross-laying in the same plane. Imitation of so specific events by natural backgrounds has negligible probability even if the detector is located in the conditions of a normal aboveground laboratory. A large mass of the working medium makes it feasible to use a natural mixture of isotopes and still can provide very high sensitivity.

**Table 1.** Experiments to search for cold dark matter with TPED detectors.

Project	Detector Mass, Total/Feducial, kg	Sensitivity, $10^{-44} \text{ cm}^2$	Location, Years on Duty	Status	Reference
XENON10	25/5 LXe	8.8 @ 100 GeV/c <sup>2</sup> 5.5 @ 30 GeV/c <sup>2</sup>	GS, 2006/2007	Completed	[37]
XENON100	100/10 LXe	0.2 @ 100 GeV/c <sup>2</sup>	GS, 2008/2009	Completed	[41]
XENON1T	3500/1300 LXe	$4.1 \times 10^{-3}$ @ 30 GeV/c <sup>2</sup>	GS, 2014	Completed	[42]
XENONnT	5900/4000 LXe	$1.4 \times 10^{-4}$ @ 50 GeV/c <sup>2</sup>	GS, 2020	Active	[40]
DARWIN	50,000/4000 LXe	$\sim 10^{-5}$ @ 5 GeV/c <sup>2</sup>	GS, 2023	Project	[36]
ZEPLIN II	31/8 LXe	66 @ 55 GeV/c <sup>2</sup>	BM, 2006/2007	Completed	[43]
ZEPLIN III	12/6.5 LXe	0.18 @ 55 GeV/c <sup>2</sup>	BM, 2008/2009	Completed	[44]
LUX	370/118 LXe	0.07 @ 100 GeV/c <sup>2</sup>	H, 2009–2016	Completed	[39]
WARP10	10/2.6 Lar	75 @ 100 GeV/c <sup>2</sup>	GS, 2006–2008	Completed	[45]
WARP100	100 Lar	1 @ 100 GeV/c <sup>2</sup>	GS, 2008–2010	Completed	[45]
DarkSide-50	46 Lar	6.1 @ 100 GeV/c <sup>2</sup>	GS, 2013–2015	Completed	[46]
DarkSide-20k	23/20,000 LAr	$1.2 \times 10^{-3}$ @ 1 TeV/c <sup>2</sup>	GS, 2017	Active	[47]
LZ	7000/5600 LXe	$1.5 \times 10^{-4}$ @ 40 GeV/c <sup>2</sup>	H, 2020	Active	[35]
PandaX-I	250 LXe	3.7 @ 49 GeV/c <sup>2</sup>	CJPL, 2014	Completed	[48]
PandaX-II	580 LXe	$3.1 \times 10^{-6}$ @ 30 GeV/c <sup>2</sup>	CJPL, 2017	Completed	[49]
PandaX-4T	3700 LXe	$3.8 \times 10^{-7}$ @ 40 GeV/c <sup>2</sup>	CJPL, 2020	Active	[50]

Notes: BM—Boulby mine (England); GS—Gran Sasso Underground Laboratory (Italy); H—Homestake DUSEL (USA); CJPL—China JinPing underground Laboratory (China).

Experiments using massive working noble liquid media receive special attention for the possibility that they can detect double-beta decays of naturally abounded isotopes (LZ, PandaX-III, XENON1T). Recently, the XENON1T experiment has announced a search for an anomalous magnetic moment, using solar neutrinos, predominantly those from the proton–proton reaction [42].

The increase in the mass of the working substance of over 100 tons makes dark-matter detectors sensitive to solar neutrinos via elastic coherent neutrino scattering off nuclei. With the increasing detector mass and sensitivity, the solar neutrino interactions become an irreducible source of background for WIMP search experiments that will open a new page in solar neutrino physics.

#### 4. Accelerator Neutrino Experiments

The Deep Underground Neutrino Experiment (DUNE—joint venture of 172 scientific institutions over the world) is under construction to use high-energy neutrinos produced at the Fermilab accelerator facility and detected over a distance of 1300 km in a few detectors (optionally TPED) containing 70 kilotons of liquid argon. The set of massive liquid argon detectors will be located deep underground at the Sanford Lab in South Dakota in order to investigate muon neutrino oscillation, to test CP violation in the lepton sector, to determine the ordering of the neutrino masses and to search for new types of neutrino and for proton decay.

The DUNE collaboration has been built and is launching two prototypes of large long-range detectors, ProtoDUNE-SP (single-phase) and ProtoDUNE-DP (dual-phase), at CERN [51]. Each is approximately one-twentieth the size of the planned far detector modules but uses components identical in size to those of the full-scale module. ProtoDUNE-DP has a 6 m maximum drift length, half that used for of Proto-DUNE Dual Phase demonstrator with  $3 \times 3 \times 1 \text{ m}^3$  active volume [52]. Gas gain electron multipliers located in the gas phase and called large electron multipliers (LEMs) amplify the signal charges before they reach a multichannel horizontal anode. The gain achieved in the gas reduces the stringent requirements on the electronics noise, and the overall design increases the possible drift length, which, in turn, requires a correspondingly higher voltage. The scintillation photon detection system (PD system) is based on an array of Hamamatsu R5912-MOD20 PMTs uniformly distributed below the cathode. The PMTs have a tetra-phenyl butadiene (TPB) coating on the photocathode's external glass surface that shifts the scintillation light from deep UV to visible light. The PMTs sit on the corrugated membrane cryostat floor, on mechanical supports that do not interfere with the membrane thermal contraction.

## 5. Nuclear Reactor Neutrino Experiments

Particular interest in the use of TPED technology for neutrino detection arose when the process of elastic coherent neutrino scattering on nuclei (CEvNS) was discovered experimentally [53] being theoretically predicted 50 years ago [54,55]. The CEvNS on the atomic nucleus prevails in the interaction of neutrinos with atoms and plays an important role in the Universe in processes accompanied by intense neutrino fluxes, such as supernova explosions, during which neutrinos carry away in the form of kinetic energy about 99% of the energy released during the explosion. The dissipation of the energy carried away by neutrinos is largely controlled by the CEvNS process.

The possibility of neutrino interaction with all nucleons of the nucleus in elastic scattering is a consequence of the Heisenberg uncertainty relation: the smaller the momentum transferred to the neutrino nucleus, the larger the interaction region becomes. If its characteristic size begins to exceed the radius of the nucleus, the interaction occurs with all nucleons at once, that is, coherently. From this it follows that this process should proceed efficiently at neutrino energies not exceeding  $\sim 50$  MeV, when the coherence condition is satisfied for all scattering angles, while the cross-section of this process is proportional to the square of the number of neutrons in the nucleus, while providing a record large cross-section of the CEvNS process at heavy nuclei. At high energies, coherent scattering will also occur, but only for a selected range of small scattering angles, providing a small transfer of momentum to the nucleus.

The study of the CEvNS process opens up a unique opportunity to test the presence of "new physics" in the neutrino sector by comparing the cross-sections for the interaction of neutrinos with various nuclei predicted in the framework of the Standard Model with experimental data. An important point that stimulates experiments on recording elastic coherent scattering of reactor electron antineutrinos is the potential for its application as a fundamentally new tool for precision remote monitoring of nuclear reactors by neutrino radiation.

In the period of 2005–2021, several experiments were performed over the world in attempt to detect elastic coherent scattering of reactor neutrinos by atomic nuclei, using solid-state detectors. The most massive from this set of detectors is the 6 kg Ge detector installed by  $\nu$ GeN collaboration [56] at Kalinin NPP (Udomlya, Russia). All of these experiments had shown only upper limits for CEvNS process.

The idea of using two-phase emission detectors with a working substance mass of hundreds and thousands of kilograms with a record sensitivity to weak ionization signals (down to single electrons) to register neutrinos and dark matter particles was first proposed in Russia [31]. This proposal was realized with a development of the liquid xenon detector RED-100, which was initially planned for setting up an experiment with accelerator neutrinos at Spallation Neutron Source (Oakridge National Laboratory) and is

now being tested at the power unit No. 4 of the Kalinin NPP, with 200 kg of liquid xenon as a working substance [57]. Based on results of the RED-100 test at NPPs, there is a plan to develop a mobile version of a TPED neutrino detector for the independent monitoring of the active zone of NPP nuclear reactors.

## 6. Conclusions

Thus, the TPED technology, which was originally proposed in Russia 50 years ago, in its development has traveled along an impressive pathway, from miniature devices for methodological studies with a working substance mass of the order of a few grams to experimental physics installations with a working substance mass of hundreds of tons, used to solve fundamental problems of modern physics such as the search for dark matter in the Universe, the study of the fundamental properties of neutrinos and the search for rare nuclei decays.

At the next stage of its development, this technology will undoubtedly be used to solve important practical problems in nuclear medicine, to ensure the safety of nuclear energy production and to support international efforts toward the nonproliferation of nuclear weapons.

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