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Review of two-phase emission detectors R&D (Dedicated to the memory of Prof. Boris A. Dolgoshein)

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Abstract. This review is dedicated to the 90th anniversary of the outstanding experimental physicist Boris Anatolyevich Dolgoshein, in whose laboratory exactly 50 years ago the first two-phase emission detector has been created. Today two-phase emission detectors found the best application in the most sensitive at the moment experiments searching for cold dark matter in the form of weakly interacting massive particles (WIMPs). Multi-ton active mass WIMP detectors of the upcoming G3 generation shall become sensitive to solar neutrinos interactions, to double-beta decay of isotopes containing in the working media with naturally occurring isotope abundances. The RED-100 detector constructed at NRNU MEPhI will be used for investigation of the reactor neutrino elastic coherent scattering off xenon nuclei at the Kalinin NPP in 2021. ProtoDUNE-DP prototype emission detector (6x6x6 m³ 300 tons LAr) is currently being assembled at the CERN Neutrino Platform in support of the DUNE project focused on investigation of high energy neutrino oscillations. Thus the detector technology invented at MEPhI 50 years has demonstrated a great potential to be used in a variety of fundamental research programs.

1. Introduction

Emission of electrons from dense media has been used to detect radiation since Henry Hertz discovered the external photoelectric effect in 1887 [1]. The effect was explained by Albert Einstein as the knocking out of electrons from atomic shells by light quanta in a series of 4 articles in the oldest physics journal *Annalen der Physik* in 1905, for which he received the Nobel Prize in 1921.

At present, by the external photo effect we mean the radiation of relatively hot electrons from the near-surface layer of a photocathode, the thickness of which is less than the path of electrons before their thermalization (cooling below the value of an electron extraction potential barrier at the interphase surface) after detachment from atoms, and is about 20-30 nm. The external photoelectric effect is used in one of the most popular instrument of experimental nuclear physics - vacuum photomultiplier tube (PMT) - to register photons arising from the interaction of elementary particles with working media of various detectors. It is interesting to note that at the beginning development of PMT technology, Radio Corporation of America (RCA) - the first company to commercialize PMTs - also tried to develop gas-filled photomultipliers with gas amplification of the resulting electronic signal generated by photons of the visible and infrared ranges [2].

The emission of quasi-free electrons from massive samples of a condensed noble gas (solid xenon) was first observed by the young English physicist G.V. Hutchinson in 1948 [3]. However, neither he nor his contemporaries at that time realized the new possibilities that opened up for registrations of elementary particles when using this effect in detectors with two-phase working media.



2. Birth of the idea of two-phase emission detectors

The idea of the emission method for detecting elementary particles is the brainchild of the development of track detectors for high energy physics. In connection with a rapid development of instrumentation for high-energy physics in the 1950s-60s, it became necessary to develop a technology for recording the tracks of high-energy particles triggered by external counters that cannot be done with bubble chambers, the most popular track detectors at the time. The first detectors of this type were spark chambers [4]. Advances in spark chamber technology have led to the creation of a streamer chamber in which a spark discharge initiated by ionization electrons is quickly interrupted because of very short high voltage pulse applied to the electrode system. Electron avalanches, which have barely begun to develop at several points along the track of high-energy particles, are forming a chain of short sparks - streamers. When the discharge develops, the streamer front moves at a speed of up to 4×10^6 m/s in fields of ~ 30 kV/cm; therefore, very short (with a duration of about 10 ns) voltage pulses are required so that the streamer length does not exceed a few millimeters. Streamers are formed in the direction of the electric field, starting from the initial ionization electrons distributed along the track of the ionizing particle. A chain of streamers can be photographed, and after processing the film, allows to determine the track, i. e. the trajectory of the ionizing particle passing through the detector. A magnetic field can be added to cause the decay products to follow curved paths so that their charge and momentum can be measured.

The first operating streamer chambers were constructed 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 MEPhI. In terms of image contrast and track spatial resolution, streamer chambers were inferior to bubble chambers; however, controllability using an external trigger made it possible to use them to study the processes occurring with low probability. As a working gas for streamer chambers, mixtures of He, H₂, Ne + He, He + CH₄, D₂ + CH₄ were usually used at a pressure of 1 bar. The coordinate resolution of the streamer chamber is determined by dimensions of the streamers, which, as a rule, have a diameter of ~ 1 mm and a length of ~ 5 mm with a density of distribution along the track of ~ 10 cm⁻¹.

In 1968, Boris Anatolyevich Dolgoshein and his team built a record-sized streamer chamber with a volume of $8 \times 2 \times 1$ m³ at MEPhI in order to search for W-bosons [5]. The camera worked for many years at the U-70 proton synchrotron in Protvino and has been used to identify fast muons, measure their spectra and polarizations. Unfortunately, W-bosons were not detected by this remarkable detector due to the fact that the energy of the U-70 accelerator (that has the highest in the world the energy of accelerated particles at the time of its launch in 1967) was not high enough to produce W-boson having a mass of 80 GeV/c² as it was shown in 1983 at CERN (the 1984 Nobel Prize awarded to Carlo Rubbia and Simon van der Meer).

The authors of streamer chamber technology (A.I. Alikhanyan, T.L. Asatiani, G.E. Chikovani, V.N. Roinishvili, B.A. Dolgoshein, B.I. Luchkov) were awarded the highest scientific prize in the USSR named after Lenin for their work "Track spark chambers" with a following formula: "for the creation of a new type of track detector capable of registering complex events during the interaction" of elementary particles. Since then, attempts have been taken to develop streamer technology based on a denser-than-gas working medium at room temperature and about 1 bar pressure. In these works, the density of the working medium was increasing either by lowering the temperature of the gaseous working medium, or by using liquefied noble gases instead of gas.

At the first direction, experiments were carried out at ITEP in the laboratory headed by Valentin Aleksandrovich Lyubimov, where Igor V. Sidorov built a cryogenic streamer chamber filled with helium or mixture of 70% Ne + 30% He or hydrogen at temperatures in the range of 80-100K [6]. In these experiments, an amazing phenomenon was discovered: the visualizing voltage threshold practically did not change with decreasing temperature and increasing density of the gaseous medium, although the tracks became more compact, denser and brighter. However, the cryogenic streamer

chamber turned out to be a rather cumbersome device, which was difficult to fit into the structure of modern accelerator installations with a detector geometry closed to 4π , and therefore this R&D work did not find real applications.

B.A. Dolgoshein and his colleagues from MEPhI studied liquid argon as a possible working medium for a liquid streamer chamber. They failed to provide a streamer discharge in liquid argon, but they have found that electrons arising from the ionization of liquid argon by charged high-energy particles can be extracted from the liquid by relatively moderate (~ 1 kV/cm) electric field into the equilibrium gas phase, where their position can be determined using well-developed methods for obtaining track information in gas media. Such detectors have been called *emission detectors* [7].

3. Emission spark chamber

The first working emission detector was a spark emission chamber using liquid argon as a working medium [8]. It was a two-electrode plane-parallel ionization chamber with a gap between the electrodes of 1.6 cm. A disk alpha source of 3.5 cm diameter was installed in the center of the cathode immersed in liquid argon. The anode was made as a flat grid composed by parallel Nichrome wires of 0.2 mm diameter with a step of 0.6 mm placed in an equilibrium gas phase above a 1.4 cm thick layer of liquid argon covering the cathode. The gas phase consisted of a 50% Ar + 50% Ne mixture. Electrons resulting from the ionization of liquid argon by alpha-particles were extracted from the liquid by an electric field of 3 kV/cm strength. A voltage pulse with amplitude of 40 kV and duration of 100 ns was applied to the anode. If at this moment the electrons were approaching to some anode wire, a spark discharge was developing nearby the wire. An optically transparent window was installed above the anode and spark discharges near the anode wires were pictured using a photo camera. The image of the two-dimensional distribution of the activity of the alpha source was formed as a superposition of images of many sparks nearby the anode wires.

The emission spark chamber did not find a practical application in experimental physics, but this first successful experiment had shown that the idea of an emission chamber works and it may be possible to build a two-phase emission streamer chamber.

4. Emission streamer chamber

A two-phase emission streamer chamber was built at MEPhI by Boris Ustinovich Rodionov with his team [9]. In this detector, solid krypton in the shape of a disk of 12.5 cm diameter and 5 mm thickness at a temperature of 78 K was used as a working medium, which was frozen down on the bottom of a metal chamber that played a role of the cathode. The mesh anode was suspended 1.5 cm above the bottom of the chamber. The anode was supported by an optical window, which also served as a high-voltage insulator. The gaseous medium consisted with neon at a pressure of 1 bar. Relativistic particles passing through the solid krypton have been selected from the particle beam using a telescope of scintillation counters. The telescope generated a signal that triggered the Arkadiev-Marx high-voltage pulse generator, which applied a high-voltage pulse with magnitude of 100 kV and duration of 60 ns to the anode. Streamer tracks of relativistic particles were formed along the electronic image of the track extracted from the solid krypton by a constant electric field of 1.5 kV/cm strength.

The efficiency of this device was experimentally demonstrated in the late 1970s at the secondary beam of a proton synchrotron at the ITEP. It was shown that the device is indeed capable of visualizing tracks of 3 GeV/c pions in the form of a chain of streamers (each of ~ 0.5 mm in diameter and 2 mm long) and, at the same time, provides an unusually high density of streamers along the track (~ 1 mm⁻¹), which makes it possible to obtain a significantly improved spatial resolution compared to gas-filled streamer chambers [9].

The study of the properties of the chamber of emission streamers confirmed the earlier observation made by Sidorov *et al.* [6] that, despite the increased density of the cold working gas as compared to the gas at room temperature, the threshold field strength for the generation of streamers remains practically unchanged. It was suggested that this effect is associated with an increase in the

concentration of noble dimer molecules in the gas with decreasing temperature and increasing density of the noble gas. Since the ionization potential of dimers decreases by 1–2 eV compared to the ionization potential of atoms, the average ionization potential of the medium decreases approximately proportionally to an increase in the concentration of dimers, as a result of which the threshold electric field strength for visualizing tracks practically does not change with decreasing temperature at constant gas pressure.

A detailed study of tracks of high-energy pions revealed anomalous tracks with a very low ionization density: one streamer per 1–2 cm of track length. First, it was suggested that the emission streamer chamber registers the tracks of unusual weakly ionizing particles. However, after detailed studies it was shown that the appearance of anomalous tracks is associated with the memory effect of a two-phase medium: anomalous tracks were recorded in exactly the same place as the tracks of relativistic particles with a normal ionization ($\sim 2 \text{ MeV/g/cm}^2$) that had been detected recently. This happened due to the capture of a part of the electrons extracted by the electric field from solid krypton at the interphase surface. Due to polarization of a dense medium by the drift electric field, electrons in solid krypton are drifting in a potential well of $\sim 0.5 \text{ eV}$ depth. Nevertheless, it should be noted that namely at that time the idea of searching for exotic particles with anomalously low ionizing capability using the technology of emission chambers was for the first time formulated [10].

In the 1980s, a large emission streamer chamber *Nadezhda* was built at ITEP. This chamber had a liquid krypton working medium in shape of cylinder of 50 cm diameter and 20 cm thickness. For visualization of relativistic particles tracks a cryogenic streamer chamber of 1.5 m diameter was specially developed ([11], Fig. 6.6). *Nadezhda* was supposed to be used in an experiment to study the multiple productions of neutral pions at the annihilation of high-energy antiprotons in heavy nuclei. The ability to render tracks with this streamer camera has been experimentally tested using an ultraviolet laser. The emission unit of this chamber was used to accurately measure the radioactivity of krypton and to study the possibility of obtaining effective emission of electrons from that record in mass sample of a liquid noble gas [12, 13]. However, the detector in full assembly has never been tested due to problems with funding scientific projects in Russia in the 1990s.

5. Ionization emission detectors

In parallel with the study of the possibility of visualization of tracks of high-energy particles passing dense working media, electronic methods for observation of interactions of elementary particles with atoms of condensed noble gases have been explored, using effects of scintillation of the condensed phase and electroluminescence and gas amplification of the gas phase. Considerable efforts have been spent on investigating other possible working media for emission detectors in particularly liquid methane and other saturated hydrocarbons which exist in liquid state at room temperature (see [11] and references there are in).

In ionization mode of readout, the interaction of ionizing particles with a condensed medium is recorded by analyzing the shape of ionization signals using charge sensitive electronics connected to the detector electrode system. This method was used at early stages of investigation of electron emission properties some condensed dielectrics with intense ionization signals generated by alpha particles [3], electron accelerators [14], and X-ray tubes [15]. The process of electron emission from various condensed noble gases, as well as from saturated liquid hydrocarbons, such as hexane, isooctane, tetramethylsilane, has been investigated using simple two-electrode ionization chambers [11].

6. Emission detectors with gas amplification

The first emission detectors were designed during the epoch of explosive development of multi-wire proportional chambers (MWPC) recently invented by George Charpak [16]. Probably on this reason, in the first emission chambers, multi-wire anodes were most often used and a possibility of avalanche amplification of ionization signals around wires has been investigated. If the registration of electrons at the anode was accompanied by a spark discharge, then such events can be pictured with photo

camera through the wired anode. If it was possible to organize proportional gas amplification around anode wires, then it became possible to record useful events in electronic form.

Gas amplification techniques are traditionally used in gas detectors to record ionization signals from individual ionizing particles. One of the first emission detectors of this type was a two-electrode ionization chamber with liquid argon working medium [17]. The electronic signal was recorded using a multi-wire flat anode composed by parallel wires with a diameter of 50-200 μm . Initial attempts were made to obtain gas amplification at the wire anode in an equilibrium gas phase, but in this mode it was not possible to achieve stable gas gain of more than 500. To create conditions for higher gas gain, the wire anode was immersed into liquid argon and heated by 0.1-1A electric current in order to create a gas jacket around them and to limit the development of avalanches by the size of bubbles. In this mode, it was achieved a gas gain of up to 10^4 . However, in such a detector, the dead time increased significantly (10 ms versus 0.1 ms in gas) that was associated with the localization of positive ions inside the bubbles. Using pulsed high voltages to multiply electrons around the wires, the gas gain was increased up to 10^6 .

More successful results have been achieved using gas amplification in emission detectors filled with organic working media at room temperature. In particular, a gas gain of 3×10^4 was obtained on the wire anode in an equilibrium saturated vapor of liquid isooctane [18] and $\sim 10^3$ in a vapor of 2,2,4,4-tetramethylpentane [19].

In pure noble gases, it is relatively easy to amplify signals using a spark discharge. Any quenching organic impurities did not work properly in emission detectors, since they inevitably cool down drifting electrons in the condensed phase that dramatically decreases a probability of electron emission.

A new step in the development of this technology was undertaken by Fabio Sauli in 1997, when he invented gas electron multipliers (GEM) [20]. The detailed study of the possibility of using GEM in two-phase emission detectors showed that this technology works well with argon when using triple GEMs to achieve a gas gain up to 5000. Unfortunately, in two-phase emission detectors using liquid xenon working medium this method does not allow to obtain gas gain better than 200 [21].

The next step in the development of technology of gas amplification of signals in two-phase liquid-argon emission detectors was the development of "thick" (ThGEM) [22, 23] and "large" (LEM) [24] electron multipliers to be used in supermassive liquid argon emission detectors with relatively low gas gain of 10-20 such as considered for the DUNE experiment goaled to study long base oscillations of high-energy neutrinos [25].

7. Electroluminescent emission chambers

The development of electroluminescent emission detectors started with building miniature detectors with a working medium volume of $\sim 1 \text{ cm}^3$. Like these detectors which were used to study the scintillation and emission properties of condensed argon, krypton, xenon, methane and their mixtures [26-28]. 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 of nineteen photomultipliers [29] that was originally proposed to be used for visualization of gamma radiation fields in nuclear medicine.

Further development of this technology led to the generation of the idea of using two signals from one event in two-phase emission detectors with liquid noble gas working medium. The first signal is a scintillation (it is often called the "S1 signal") that appears at the moment of interaction of the registered particle with the condensed working medium of the detector. The second signal (often referred to as the "S2 signal") is an electroluminescence generated by ionization electrons extracted from the condensed phase by an electric field and are drifting through the gas phase. The use of these two signals when registering a quasi-point event makes it possible to determine the 3D position of the interaction point inside the detector and to create a so-called "wall-less" detector for recording rare events at some distance from the walls of the detector using a peripheral layer of a liquid noble gas as an active shielding. This method was first proposed in 1995 for the registration of dark matter particles

and low energy neutrinos [30]. The possibility of reconstructing complicated multi-particle events in a dense noble gas with S1 and S2 signals was first time demonstrated in a detector using compressed xenon as a working medium [31]. At about the same time, it was proposed to use this technology to search for rare decays such as double beta decay [32].

8. Dark Matter search

Since two-phase emission detectors are sensitive to single electrons and have a massive working medium they are appeared to be very useful to search for rare events and weakly ionizing particles such as hypothetical Weakly Ionizing Massive Particles (WIMP) of dark matter. This idea for the first time was formulated in 1989 [33].

Up of today the world's best results in the search for cold dark matter in the form of WIMPs have been obtained using two-phase emission detectors with xenon working medium and the registration of two signals from one event. Modern two-phase emission detectors are using up to 10 tons mass of working medium [34, 35]. The next generation of dark matter detectors of this type will have a mass of liquid xenon or argon working medium up to 50-200 tons [36].

9. Neutrino detection

Recently, two-phase emission detectors have also begun to be considered for studying properties of relatively low energy reactor neutrinos using an effect of elastic coherent scattering off heavy nuclei [37]. In case of success this kind of very effective neutrino detectors may be used for independent monitoring nuclear reactors in support of safety and for support of international non-proliferation programs [38].

Two-phase liquid argon emission detector with a capacity of 10 kilotons is one of the four detectors considered for the Deep Underground Neutrino Experiment (DUNE) focused on long baseline neutrino oscillation studies, neutrino astrophysics and rare nucleon decay searches. DUNE will compose four 10 kton fiducial liquid argon time-projection-chamber (LAr TPC) modules placed at the Sanford Underground Research Facility (South Dakota, USA) in order to detect high energy neutrino generated 1300 km away at the Fermilab accelerator facility. One of these modules will profit from the two-phase emission (or dual phase – DP – TPC as often called in modern Western publications) technology where the charge is extracted, amplified, and detected in gaseous argon above the liquid surface allowing a fine readout pitch, a low energy threshold, and good pattern reconstruction of the events. To gain experience in building and operating such a large-scale two-phase emission detector, the ProtoDUNE-DP prototype detector (6x6x6 m³ 300 tons LAr) is currently being assembled at the CERN Neutrino Platform [39].

10. Conclusion

Thus, the technology of two-phase emission detectors during 50 years of its development has gone an impressive way from miniature detectors with a working medium mass of about one gram for R&D purposes to multi-ton detectors for solving fundamental problems of modern physics. At the next stage of the development, this technology can also be used to solve important practical problems related to improving the safety of nuclear power generation (independent neutrino monitoring of the reactor core) and to supporting international efforts for the non-proliferation of nuclear weapons (independently monitoring the isotopic composition of nuclear fuel in reactors).

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