

## Chapter 1

# Hetero-phase Detectors and History of Development of Emission Detectors

Properties of detectors used to detect, track and identify high-energy particles and radiation directly depend on the properties of their working media. Effective detection of low-ionizing and highly penetrative radiation is only possible with working media of sufficient mass and density. However, the amount of energy deposited by detected radiation is typically very small and special measures are needed to amplify signals generated by interactions of detected radiation with the detector's working media. There are several approaches for measuring the small amount of energy deposited in large mass detectors (see, for example, a classic monograph by Glenn F. Knoll). In this chapter, we focus our attention to a class of detectors utilising specific properties of hetero-phase working media in which detected radiation interacts with a condensed medium but signals are generated in the rarefied phase co-existing with the condensed medium or signals are generated in result of phase transitions.

### 1.1 Photo-emission detectors

The *photo-electric effect* is a quantum electronic phenomenon in which electrons are emitted from matter after the absorption of energy from electromagnetic radiation such as X-rays or visible light. The emitted electrons can be referred to as *photo-electrons* in this context. The effect was termed the *Hertz effect* after Heinrich Rudolf Hertz discovered in 1887 that UV radiation ignites spark between charged zinc electrodes. Further study of the effect led to understanding the quantum nature of light and to development of various detectors of photons and

ionizing particles. In the months following Hertz's discovery, Alexander Stoletow investigated the photo-electron emission from different materials at different conditions (pressure and temperature) and found the electron emission from liquid solutes and Augusto Righi discovered photo-electron emission from solid dielectrics.

In 1902, P.E.A. von Lenard observed that the energy of the emitted electrons increased with the frequency, or colour, of the light. This was at odds with J.C. Maxwell's wave theory of light, which predicted that the energy would be proportional to the intensity of the radiation. The big surprise was that the photo-electric effect only occurs when a metallic surface is exposed to electromagnetic radiation above a certain threshold frequency. In 1905, Albert Einstein found a way to solve this paradox by describing light as composed of discrete quanta (photons) rather than continuous waves. Using M. Planck's theory of black-body radiation, Einstein theorised that the energy in each quantum of light was equal to the frequency multiplied by a constant, later called Planck's constant. A photon above a threshold frequency has the required energy to eject a single electron, creating the observed effect. This discovery led to the quantum revolution in physics and earned Einstein the Nobel Prize in 1921.

The discharge device of Hertz could be considered as the first emission detector sensitive to UV radiation. Since the discovery in the late 1920s that electrons accelerated in vacuum may cause emission of secondary electrons and as a result provide amplification of the electron signal, photo-multipliers begin their distinguished history. Photo-electron multiplier tubes (PMT) based on the multi-stage amplification of a photo-electron signal was invented by L.A. Kubetsky in 1930 and re-invented by V. Zworykin in 1936. Since that time photo-emission detectors received a long and well-proven record in experimental physics, nuclear medicine, oil well logging, monitoring nuclear materials and many other important technical applications.

## **1.2 Cloud chambers**

At the boundary between the 19th and 20th centuries, Scottish physicist Charles T.R. Wilson, studying cloud formation and optical

phenomena in moist air, discovered that ions could act as centres for water droplet formation (see, for example, excellent review by Henderson, 1970). Wilson built a chamber filled with saturated vapour of water-alcohol mixture and connected it to an expansion mechanism. By rapidly reducing the pressure, the gas inside the chamber undergoes an adiabatic expansion and cools; supersaturated vapour condenses in liquid droplets on centres of nucleation, which could be dust or ions. The condensation of liquid along tracks of ionizing particles makes them visible. Many physicists experimented with such devices. In 1924, Peter L. Kapitza placed the *Wilson chamber* in a strong magnetic field that allowed measurements not only the charge but also the momentum of particles analysing curvature of their tracks. The new approach led Carl D. Anderson to discovery of the positron in 1932 (winning him the Nobel Prize in Physics for 1936) and the muon in 1937 in cosmic rays.

Wilson, along with A.H. Compton, received the Nobel Prize for Physics in 1927 for his work on the cloud chamber. This kind of chamber is also called a *pulsed chamber*, because the conditions for operation are not continuously maintained.

In fact, the Wilson chamber was the first device using a two-phase (saturated vapour and liquid droplets) working medium for detection and visualisation of tracks of individual particles. Since then, diffusion, spark and streamer cameras have been developed for visualisation of particle tracks in gases at normal pressure. With the ever increasing energies of investigated particles, condensed working media have been considered for construction of more sensitive devices.

### **1.3 Bubble chambers**

A *bubble chamber* is an extension of the idea of cloud chamber to denser working media (see, for example, a great review by Aleksandrov *et al.*, 1967). The bubble chamber was invented by Donald Glaser in 1952, when he has shown that ionizing radiation could initiate boiling in superheated liquids. Soon after that he succeeded in photographing a string of vapour bubbles induced by the passage of an ionizing particle through a superheated liquid. The dramatic difference in optical density between liquid and vapour was used to photograph tracks of high-energy

particles interacting with liquids. The bubble chamber become the second example of a detector using a two-phase (liquid and saturated vapour in bubbles) working medium. In 1960, Glaser received a Noble Prize for the development of bubble chambers.

The first physical results with bubble chambers were obtained with 'clean' bubble chambers made of glass. One reason for this approach is that the surface of the glass is free from microscopic defects that may become centres for the initiation of boiling of the liquid. In addition, glass chambers may be made without seams or seals. However, with technological improvements, tracks were soon successfully observed in 'dirty' chambers made of a polished metal body and flat glass windows sealed with Teflon. Eventually, most of the cryogenic liquids found application in bubble chambers, with helium and xenon among them (Table 1.1). Light liquids allow using magnetic fields in order to determine the momentum of charged particles from the curvature of their tracks. The heavy liquids are attractive because of their efficient absorption of gamma radiation. Since heavy noble liquids are the most popular working media of modern two-phase emission detectors, we refer to liquid xenon bubble chambers as a direct prototype of the emission detectors.

Table 1.1 Properties of bubble chamber liquids (Harigel, 2003; Henderson, 1970).

Liquid	Temperature, K	Vapour pressure, bar	Density, g/cm <sup>3</sup>	Radiation Length X <sub>0</sub> , cm	Absorption Length λ <sub>0</sub> , cm
He	3.2	0.4	0.14	1027	437
H <sub>2</sub>	25	4	0.0645	968	887
D <sub>2</sub>	30	4.5	0.14	900	403
C <sub>3</sub> H <sub>8</sub>	333	21	0.43	110	176
Ne	35	7.7	1.02	27	89
Ar	135	28	1.0	20	84
CF <sub>3</sub> Br	303	21	1.5	11	73
Xe	253	26	2.2	3.9	56

Xenon, being predominantly a monatomic medium, has no rotational or vibration atomic oscillation modes, and as a result, it is effectively converting the energy of  $\delta$ -electrons into light (scintillation). To convert the energy of scintillation into localised heat and enhance the formation

of bubbles, molecular admixtures of ethylene or propane have been used in LXe bubble chambers (see references in Table 1.2)

Table 1.2 Liquid xenon bubble chambers.

Built	Temperature, K	Density, g/cm <sup>3</sup>	Working Volume	Reference
1950s	254	2.3	Ø2.5·1.3 cm <sup>2</sup>	Brown <i>et al.</i> , 1956
1950s	254	2.2	Ø30·25 cm <sup>2</sup>	Brown <i>et al.</i> , 1961
1960s	260	1.4	180 litres	Barmin <i>et al.</i> , 1972
1970s	260	1.4	1.5·0.7·0.7 m <sup>3</sup>	Barmin <i>et al.</i> , 2003

The first liquid xenon bubble chamber was built by Glaser in the 1950s, the largest and the most successful *DIANA LXe bubble chamber* was built at ITEP (Moscow) in the 1970s (Fig. 1.1). Images acquired from LXe bubble chambers allow for the reconstruction of topologically complicated events, including large number of  $\gamma$ -quanta and  $\pi^0$ -mesons. DIANA was decommissioned in 1985 but a data analysis from about 1 million stored images is still continuing. Using this archive, ITEP scientists recently reported the discovery of exotic *pentaquark* resonance generated in low-energy  $K^+Xe$  collisions (Barmin *et al.*, 2003).

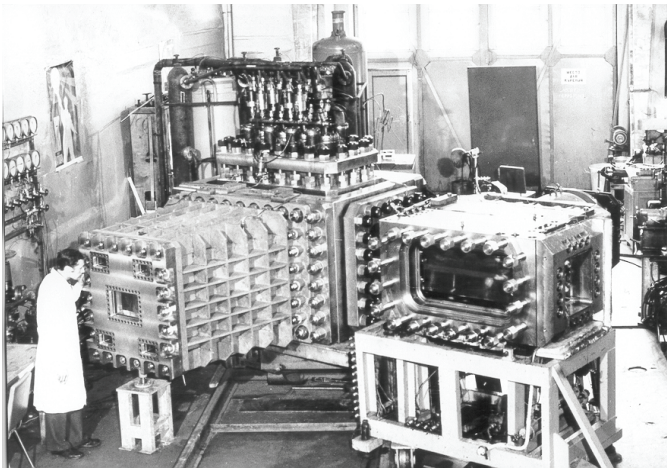


Figure 1.1 Liquid xenon bubble chamber DIANA with 1.5x0.7x 0.7 m<sup>3</sup> active volume constructed at ITEP in the 1970s. Courtesy of A.G. Dolgolenko.

In an attempt to improve the performance of bubble chambers and integrate them into multi-detector systems with sophisticated triggers for high energy experiments, the use of the scintillation properties of some liquids was considered. One of the first bubble chambers of this type was a three-litre chamber filled with liquid propane to which a naphthalene wave-shifter was added (Minehart and Milburn, 1960). From this work, it was shown for the first time that scintillation and bubble nucleation are not necessarily mutually exclusive. Later, the use of a scintillation trigger and the collection of charge during the expansion cycle in a liquid argon bubble chamber were considered by Berset *et al.* in 1982. The amplitude of the scintillation trigger can give preliminary information about the energy deposited by electromagnetic or hadronic showers; the scintillation signal can be used to trigger a laser beam to initiate marker tracks simultaneously with useful events.

These first attempts demonstrated that bubble chamber technology would not be easily integrated into fast detectors with an electronic readout. That was the original motivation to explore new approaches in detector technology based on condensed working media and electronic *filmless imaging*.

At the beginning of the 21st century, bubble chambers again attracted the attention of particle physicists, who, at this time, were interested in searching for cold dark matter in the form of weakly ionizing massive particles (WIMPs; Bond *et al.*, 2005). At the University of Chicago, it was shown that, for certain pressure and temperature operating conditions, the vaporisation of the overheated liquid can only be produced by particles having a large stopping power, such as nuclear recoils, making the detector insensitive to most minimum ionizing backgrounds due to gamma radiation (Collar *et al.*, 2000). The devices are operated at near room temperature and use non-flammable, non-toxic and inexpensive liquids, with a chemical composition (e.g.  $\text{CF}_3\text{I}$ ) that provides maximum sensitivity to neutralino interactions through both the spin-dependent and spin-independent channels.

## 1.4 Electron emission detectors

The development of emission detectors has a long history. The first emission detector was probably Hertz's spark gap triggered with ultra-violet radiation (1887). The discovery of photo-electron emission from metals eventually led to an understanding of the quantum nature of light and the development of the quantum age in modern physics. Since then, the effect has been successfully used in vacuum photo-diodes and photo-multipliers to detect low-intensity photon fluxes or even single photons for a variety of technical applications. The discovery of electron emission from dielectrics by Stoletow and Righi extended the technology for massive detection media and made it possible to detect extremely low-ionizing radiation and very rare particle interactions.

The next important step was made only half a century later, in 1948, after the discovery (Davidson and Larsh, 1948) that ionization electrons can live long enough in condensed argon to be collected from the bulk material and their charge to be measured. The first electron emission two-phase (solid and gas argon) detector was constructed by a graduate student, G.W. Hutchinson, in 1948 (Hutchinson, 1948). However, the advantages of the new approach were not fully recognised at that time by the detector science community, and the idea was forgotten for about 20 years.

The advantages of condensed noble gases for precision imaging and for the development of detectors for high energy particles were recognised by L. Alvarez in 1968. The development of liquid xenon ionization chambers by L. Alvarez, H. Zaklad, S. Derenzo at Lawrence Berkley National Laboratory, in the 1960s and 1970s, seemed to open a way for digital imaging 140–511 keV gamma rays for nuclear medicine needs with noble gas detectors.

Independently of Alvarez, the possibility of using condensed noble gases as working media for particle detectors attracted the attention of B.A. Dolgoshein and his co-workers at Moscow Engineering Physics Institute. They were led by B.U. Rodionov, who rediscovered electron emission from liquid argon and observed electroluminescence of pure noble gases in the course of attempting to develop a high-density *streamer chamber*. They proposed using the properties of noble gases to

develop highly sensitive imaging instrumentation with electronic readout — *emission detectors* (Rodionov, 1969; Dolgoshein, Lebedenko and Rodionov, 1970). Since then, new emission detector media have been discovered and a variety of different emission detectors has been developed as described in this book. In general, it was shown that emission detectors can combine the high detection efficiency inherent to dense and massive working media with high gain through the physical amplification of electron signals that is only possible in the rarefied phases (Rodionov, 1969, 1987).

The first attempts to construct emission detectors were focussed on developing imaging cameras to visualise tracks of individual relativistic particles in high energy physics experiments (Bolzdynya *et al.*, 1977). However, soon after a successful test of the first emission streamer chamber at the ITEP proton synchrotron, it was understood that the long drift time required to operate emission cameras drastically limited their utility in experiments in modern high-luminosity accelerators.

After that, the emission method was explored for imaging gamma radiation for nuclear medicine applications (Egorov *et al.*, 1983). The first attempt to develop such a gamma camera was quite successful and a group of young physicists (S. Kalashnikov, V. Egorov and A. Bolzdynya), working on the development of an emission electroluminescence gamma camera, received an award from the USSR Academy of Science in 1984.

With the development of *non-accelerator physics* and *low-background experiments* searching for rare nuclear decays and exotic particles, it became clear that, in this field, emission detectors can demonstrate all their advantages, including the possibility of constructing ‘wall-less’ detectors with large mass and low detection threshold (Bolzdynya *et al.*, 1995). In the relatively short period that has passed since that time, emission detectors have filled a unique niche in the arsenal of modern instrumentation for experimental and applied physics. It is quite notable, that for the last thirty years, emission detector technology has developed from the miniature R&D devices of about 1 cm<sup>3</sup> sensitive volumes to multi-tonne detectors, as described in Chapter 8.