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Introduction

Progress in experimental nuclear and particle physics and their applications in medicine, geological exploration, and industry has always been closely linked with improved methods of radiation measurement.

This book will review the physical properties of noble fluids, operational principles of detectors based on these media, and the most innovative technical design approaches yet developed to optimize these detectors. This subject area has developed through the research of many groups from different countries and continents. Many outstanding physicists and nuclear engineers have contributed to the development of noble fluid detectors. Among them there are Nobel laureates Glaser (1960), Alvarez (1964), and Charpak (1992).

In this monograph, extensive attention is devoted to detector technology: purification and purity monitoring methods, information readout methods, electronics, detection of far ultraviolet light emission, selection of materials, cryogenics, etc. This book is intended to provide all the information necessary for understanding the construction of pure noble gas-filled detectors, it might serve as a handbook on the properties of noble gases and liquids. Numerous cited publications are provided to allow readers to delve more deeply into any of the subjects touched upon in this book.

1.1
Units and Definitions

SI is the favored system of units throughout this text, although in experimental nuclear and elementary particle physics, energy is conventionally measured in units of electron volts and gas pressure is measured in Torr, bar or atmospheres, and these units will be frequently employed when describing these quantities. To aid readers wishing to cross reference values encountered in their reading, we have tabulated many of the physical quantities used throughout the text in Table 1.1.

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Tab. 1.1 Fundamental constants, symbols and units used in the book.

Quantity	Symbol, equation	Value or conversion formula
Avogadro's number	N_A	$6.0221\times10^{23}\text{mol}^{-1}$
Bohr magneton	μ_B	9.27×10^{-24}J/T = 5.79×10^{-5} eV T^{-1}
Boltzman constant	k	1.381×10^{-23} JK^{-1} =8.617×10^{-5} eV K^{-1}
Capacitance	C	1 F = 1 C V^{-1} = 10^{12} pF
Concentration	K	1 ppm = 10^{-6}; 1 ppb = 10^{-9}; 1 ppt = 10^{-12}
Density	ρ	1 kg m^{-3} = 0.001 g cm^{-3} = 6.243×10^{-2} lb ft.^{-3}
Electric field strength	E	1 kV cm^{-1} = 10^5 V m^{-1} = 10^5 N C^{-1}
Elementary charge	e	1.60×10^{-19} C
Electron rest mass	m_e	9.11×10^{-31} kg
Energy	E	1 eV = 1.602×10^{-19} J = 1.60×10^{-12} erg
		1 J = 0.2388 cal
Length	l	1 m = 39.4 in. = 3.28 ft.
		1 in. = 2.54 cm = 25.4 mm; 1 mi = 1.61 km
Magnetic field	B	1 T = 1 Wb m^{-2} = 10^4 gauss
Mass	m	1 g = 10^{-3} kg = 10^{-6} ton (metric) = 6.02×10^{23} u
		1 u = 1.661×10^{-27} kg
Permittivity constant	ε_0	1.26×10^{-6} F m^{-1}
Pressure	p	1 atm = 1.013 bar = 760 Torr = 1.03×10^5 Pa = 14.7 psi
		1 Torr = 1 mmHg = 133.32 Pa
		1 Pa = 1 N m^{-2} = 9.869×10^{-6} atm = 1.45×10^{-4} lb in.^{-2}
Radioactivity	$\text{d}N/\text{d}t$	1 Bq = 1 disintegration/s = 2.703×10^{-11} Ci
Speed	v	1 m c^{-1} = 100 cm s^{-1} = 3.6 km h^{-1} = 2.237 mi h^{-1}
Speed of light	c	299 792 458 m s^{-1}
Temperature	T	K = °C + 273.16; °F = 1.8×(°C) + 32; °R = °F + 459.67
Time	t	1 s = 1/60 min = 1/3600 h; 1 d = 86 400 s
		1 y = 365.2 d = 3.16×10^7 s; 1 ns = 10^{-9} s; 1 µs = 10^{-6} s
Volume	V	1 m^3 = 103 L = 106 cm^3 = 264.2 US gallons
Wavelength	λ	1 nm = 10^{-9} m = 10Å

1.2
Brief History of Noble Gas Detectors

The first device used to detect ionizing radiation was the eighteenth century gas (air) ionization chamber known as a gold-leaf electroscope. Since Becquerel's discovery of radioactivity in 1896, the electroscope has been used to measure the integral flux of ionizing radiation. Thomson received a Noble Prize in Physics in 1906 for his study of the electrical conductivity of ionized gases. In 1897, Thomson reported on the increasing conductivity of Vaseline oil irradiated by X-rays [1]. This was the first example of an ionization chamber working with a condensed dielectric. Soon thereafter, Curie observed a similar effect due to the influence of radium radiation in several nonpolar liquids [2]. In 1908, Rutherford and Geiger developed a cylindrical pulse ionization chamber for the detection of individual subatomic particles. A few years later, Geiger built his very sensitive gas-discharge particle counter [3, 4] that was used in experiments leading to the identification of the alpha particle with the nucleus of the helium atom [5] and to the development of Rutherford's model of the atom. Between 1928 and 1929 Geiger and Mueller constructed large sensitive area counters, and they have since been called Geiger–Mueller counters [6, 7]. The next important step was the development of proportional counters that provided a means to identify particles based on their inherent ionization ability [8].

The first position-sensitive device for particle track visualization was the "cloud" chamber built by Wilson in 1912, which for decades served as a workhorse in experimental particle physics. Later, diffusion, spark, and streamer cameras were developed to visualize individual particle tracks in gases at atmospheric pressure. Noble gases played an important role in all these developments, serving as "fast" fill gases. With the ever-increasing energies of particle interactions being explored, coupled with the development of sensitive electronic amplifiers, detectors with liquid and solid working media were gradually introduced into elementary particle research. The development of imaging detectors culminated with the introduction of bubble chambers (including some employing liquid xenon) by Glaser, who received the Noble Prize in Physics in 1960 for this development.

Noble gas detector development entered a new era beginning in the late 1940s when Davidson and Larsh observed the appearance of electron conductivity in liquid argon that was initiated by the absorption of radiation in that medium [9]. Almost immediately thereafter, Hutchinson (1949) confirmed the observation of highly mobile ionization electrons drifting in liquid and solid argon and for the first time reported on detection particles in a two-phase electron emission detector [10].

At the beginning of the 1950s, liquid (LAr) ionization chambers, employing a Frisch grid, were used in a major nuclear physics experiment [11, 12]. Attention later focused on the excellent scintillation properties of condensed noble gases [13, 14].

During the 1950s and 1960s, significant effort was expended on investigations into the electron transport properties of pure noble gases and gas mixtures used for efficient electron multiplication in wire chambers. The multiwire proportional chamber (MWPC), invented by Charpak in 1968, has undergone tremendous development after the introduction of digital signal processing, integrated electronic circuits and computers. Since that time practically every experimental installation in high-energy physics incorporates MWPCs, allowing for the discovery of new particles such as J/Ψ by Ting and Richter or the W and Z by Rubbia, who won Nobel Prizes in 1976 and 1984, respectively. For the invention of these electronic detectors Charpak was awarded a Noble Prize in Physics in 1992.

Charpak and his collaborators (Sauli, Majewski, Policarpo, Ypsilantis, Breskin) have originated many innovative noble gas detectors such as gas-filled drift chambers, proportional scintillation chambers, parallel plate avalanche chambers, and they pioneered the development of X-ray digital imagers for medicine, biology and industry.

The advantages of condensed noble gases for precision imaging and for the development of high-energy particle and radiation detectors was recognized by Alvarez in 1968 [15]. Following the development of liquid xenon ionization chambers by Alvarez, Zaklad, Derenzo and others during the 1960s and 1970s, it was realized that such devices could be utilized in the field of nuclear medicine due to their potential for imaging 140-511 keV gamma rays.

Independently of Alvarez and his colleagues in the West, Russian and Japanese scientists explored condensed noble gases as working media of particle detectors. Doke and coworkers initiated a study of the fundamental properties of liquid rare gases that led to their determination of the W-values and values of the Fano factor, decay times and light yield of scintillations for heavy noble gases, etc. Dolgoshein and coworkers, in the course of their attempts to develop a liquid noble gas streamer chamber, observed secondary electron emission and electroluminescence, leading them to propose using these processes to develop new, highly sensitive instrumentation with imaging capabilities.

During the 1970s and 1980s, liquid noble gas calorimeters were constructed to detect high-energy electromagnetic radiation at several major laboratories around the world, among these were: the Institute of High-Energy Physics (Serpukhov, Russia), CERN, and the Budker Institute (Novosibirsk). The ICARUS group headed by Rubbia developed a LAr TPC for solar neutrino detection. Later, a few groups from the US, Russia, Japan, and Europe (CERN) investigated the possibility of building homogeneous electromagnetic calorimeters, where passive particle absorption and signal detection are combined within one material.

At the beginning of the 1980s, it was recognized that the energy resolution of noble liquid ionization detectors is much worse at low energies than predicted from ionization statistics, and researchers turned their attention to the development of high-pressure gas detectors, which have better intrinsic resolution at low energies. Two methods were developed for extracting information from these detectors. The more conventional technique is to measure the charge liberated by ionizing radiation. Alternatively, one can measure the light emitted by ionization electrons drifting in sufficiently high electric fields. This process, called electroluminescence (EL) or proportional scintillation, was originally investigated by Policarpo and Conde in the 1960s.

Initially, the difficulty of achieving sufficient noble gas purity necessary for transporting electrons over large distances inhibited the development of noble fluid based detector technology. A solution to the problem of effective xenon purification in the 1990s opened the way for developing precision gamma ray spectrometric instrumentation for observational astronomy, nuclear safeguard applications, and medical imaging. At the beginning of the twenty-first century, huge noble liquid ionization calorimeters are working at many accelerator laboratories across the world, liquid argon time projection chambers containing many tons of fluid are used for the study of solar neutrinos, scintillation detectors and two-phase emission detectors containing tons of noble fluid are under intensive development for rare events and exotic particles searches, and several groups continue to pursue the development of new instrumentation for nuclear medicine imaging. The authors of this book believe that the best pages of the history of noble gas detectors are yet to be written.