Elena Aprile, Aleksey E. Bolotnikov,
Alexander I. Bolozdynya,
and Tadayoshi Doke

Noble Gas Detectors

WILEY-VCH Verlag GmbH & Co. KGaA

Elena Aprile, Aleksey E. Bolotnikov,
Alexander I. Bolozdynya,and
Tadayoshi Doke

Noble Gas Detectors

Related Titles

Grob, R. L., Barry, E. F. (eds.)

Modern Practice of Gas Chromatography

1045 pages

2004. Hardcover

ISBN 0-471-22983-0

Tschulena, G., Lahrmann, A. (eds.)

Sensors in Household Appliances

Sensors Applications Vol. 5

310 pages with 153 figures and 32 tables

2003. Hardcover

ISBN 3-527-30362-6

O'Hanlon, J. F.

A User's Guide to Vacuum Technology

550 pages

2003. Hardcover

ISBN 0-471-27052-0

Knoll, G. F.

Radiation Detection and Measurement

816 pages

2000. Hardcover

ISBN 0-471-07338-5

Turner, J. E.

Atoms, Radiation, and Radiation Protection

575 pages

1995. Hardcover

ISBN 0-471-59581-0

Zucker, R. D., Biblarz, O.

Fundamentals of Gas Dynamics

512 pages

2002. Hardcover

ISBN 0-471-05967-6

Elena Aprile, Aleksey E. Bolotnikov,
Alexander I. Bolozdynya,
and Tadayoshi Doke

Noble Gas Detectors

WILEY-VCH Verlag GmbH & Co. KGaA

The Authors

Dr. Alexander I. Bolozdynya
Case Western Reserve University
Department of Physics
10900 Euclid Avenue
Cleveland, OH 44106-7079
USA

Prof. Elena Aprile
Columbia University
Physics Department & Astrophysics Laboratory
550 West 120th Street
New York, NY 10027
USA

Dr. Aleksey E. Bolotnikov
Brookhaven National Lab.
Bldg. 197-D
Upton, NY 11793
USA

Prof. Tadayoshi Doke
Waseda University
1-104 Totsukamach
Shinjuku-ku
169-8050 Tokyo
Japan

Library of Congress Card No.:
applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Typesetting Uwe Krieg, Berlin
Printing Strauss GmbH, Mörlenbach
Binding Littges & Dopf Buchbinderei GmbH, Heppenheim

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN-13: 978-3-527-40597-8
ISBN-10: 3-527-40597-6

Foreword

This book is a welcome addition to the literature available to those of us interested in the spectroscopy and imaging of ionizing radiation. The subset of detectors based on dense noble gases as the active medium has grown in diversity and importance over the past several decades. The material included here is both comprehensive and authoritative. Each of the authors has a distinguished research record that has helped advance the field. They provide a unique perspective and expertise that is reflected in the high-quality discussions of principles and devices that will be found throughout the book.

Noble gases in compressed or liquid form are regarded as an attractive detection medium from several standpoints. Detector volume is not limited by the need for crystal growth required in many alternative approaches, and the statistical limit on energy resolution is quite small due to moderate values for average ionization energy and a relatively low Fano factor. These media also show a scintillation yield that can be a primary or supplemental output signal. These properties are reviewed and thoroughly documented throughout the book with useful and current literature citations. The types of detectors discussed cover the use of noble gases in liquid, high pressure, and two-phase states. These media are incorporated into devices based on various strategies to generate output signals, including direct collection of ionization charges, proportional multiplication of that charge, or the collection of scintillation light.

The world of radiation detection and imaging has historically been dominated by requirements set by the physics and medical imaging communities. With the emergence of new needs for environmental monitoring and remote detection of radiation, there is an increasing need to expand the horizon of technologies and instruments available for these applications. This monograph will play an important role in providing a basic scientific and technical foundation for some of the development efforts that will be required in the future.

Ann Arbor, Michigan, June 2006 *Glenn F. Knoll*

Contents

Preface

This book is the first monograph exclusively dedicated to a new class of radiation detectors developed in the past three or four decades. Pure compressed noble gases (He, Ne, Ar, Kr, and Xe) and their liquids have a unique combination of physical properties such as high stopping power, small Fano factor, and relatively low energy required for electron–ion pair and photon production (xenon), high thermal neutron absorption cross section (^{3}He), low Doppler broadening in Compton scatter (neon) etc., making them very suitable radiation detection media. Moreover, pure noble gases are available in large quantities and noble gas detectors are scalable, allowing the construction of large detectors that operate in accordance with principles explored using small prototypes. Noble gases are relatively cheap (the current market price of the most expensive of them, pure xenon, is about $1 per gram), and their annual production levels are measured in many tons.

For the last two decades of the twentieth century, considerable efforts were devoted to developing noble gas gamma ray spectrometers, gamma ray and X-ray imaging devices, Compton cameras, luminescence cameras, high-energy electromagnetic calorimeters based on liquefied noble gases, and two-phase emission detectors. New challenges of the twenty-first century, related to nonproliferation and antiterrorism, have drawn more attention to noble fluid detectors. The detection and monitoring of nuclear materials demand highly reliable and sensitive nuclear radiation detection systems. Recently, it was demonstrated that high-pressure xenon ionization chambers could tolerate the full range of environmental extremes seen in nature and operate as gamma spectrometers, approaching room temperature semiconductor detectors in performance. Recent advances in the development of noble fluid detectors and associated technologies have led to the planning of several new experiments of fundamental scientific significance such as the search for cold dark matter in the universe, the measurement of neutrino mass through neutrino-less double beta decay, the measurement of the neutrino magnetic moment.

This book is primarily addressed to physicists and graduate students involved in the preparation of the next generation of experiments in fundamental physics, nuclear engineers developing instrumentation for nuclear security, and for monitoring nuclear materials. The book may serve as a textbook for beginners as well as a practical manual for experienced detector physicists planning construction of noble gas detectors with extremely pure, dense and massive working media. Detector physics is a subject of interest in nuclear engineering, experimental nuclear and high-energy physics courses in several distinguished universities, among which can be counted Columbia University, MIT, Princeton University, UCLA, and the University of Michigan in United States, Waseda University in Japan, MEPI in Russia. This book will also provide students in health physics, environmental protection, radiation biology, and nuclear chemistry with a useful glimpse into an exciting and important area of modern radiation detector technology.

August 2006 *E. Aprile, A. E. Bolotnikov, A. I. Bolozdynya, and T. Doke*

Acknowledgements

This book represents a distillation of more than 120 years of total experimental experience of the authors distributed over almost 40 calendar years, beginning from the 1960s. The authors would be happy to individually acknowledge all the colleagues who shared the hard work in the development of the technology of noble gas detectors over this period. However, they cannot be absolutely sure that all names are recalled. For this reason, they would like to dedicate this monograph to all experimentalists working on novel detector developments.

Daniel McKinsey, Vitaly Chepel and Pavel P. Brusov, Robert Austin, Karl-Ludwig Giboni, Carl E. Dahl, Toshinori Mori, Satoshi Suzuki are thanked for their critical reading of the book and many valuable suggestions. Satoshi Mihara and Guillaume Plante are thanked for helping prepare illustrations in Chapter 9. The input of the graduating students in the US, Russia, and Japan is difficult to overestimate.

Many figures and tables in this monograph have been previously published elsewhere as indicated in captions and references. The authors acknowledge cooperation of the following publishers in granting permissions for reproduction of these materials:

Nuclear Instruments and Methods in Physics Research
Copyright © by Elsevier. Figures 2.5, 2.11, 2.12, 2.13, 3.47, 3.50, 4.5, 4.6, 4.7, 4.15, 4.16, 4.21, 4.22, 5.7, 5.8, 5.9, 5.12, 5.14, 5.15, 5.17, 5.18, 5.19, 5.30, 6.4, 6.5, 6.6, 6.7, 6.9, 6.10, 6.11, 6.18, 6.19, 6.20, 6.21, 6.26, 6.27, 7.5, 7.8, 7.10, 8.2, 8.3, 8.5, 8.6, 8.7, 8.8, 8.9, 8.10, 8.12, 9.7, 9.8, 9.9, 9.10, 9.12. Tables 5.1, 8.2.

Physics Letters
Copyright © by Elsevier. Figure 3.24.

Nuclear Physics B – Proceedings Supplements
Copyright © by Elsevier. Figure 9.8.

IEEE Transactions
Copyright © by The Institute of Electrical and Electronics Engineers, Inc., New York. Figures 2.3, 2.4, 3.2, 3.19, 3.23, 3.25, 3.53, 3.54, 4.2, 4.3, 4.8, 4.9, 4.10, 4.11, 4.12, 4.13, 4.14, 4.17, 4.18, 4.19, 4.20, 4.21, 5.19, 5.20, 5.21, 5.22, 5.23, 5.24, 5.25, 6.1, 6.12, 6.13, 6.14, 6.17, 7.9, 7.11, 9.11, 9.15. Tables 3.8, 8.4.

Physical Review
Copyright © by the American Physical Society, New York. Figures 3.14, 3.30, 3.31, 3.34, 3.35, 3.36, 3.37, 3.42, 3.44, 3.45, 3.46, 3.48, 3.49, 5.26, 9.9. Tables 3.10, 3.14, 3.15.

Journal of Chemical Physics
Copyright © by the American Physical Society, New York. Figure 3.33.

Japanese Journal of Applied Physics
Copyright © by the Japan Society of Applied Physics. Figures 4.22, 4.23, 4.24, 4.25, 4.26, 5.27. Table 8.3.

Journal Physics B: Atomic, Molecular and Optical Physics
Copyright © by the Institute of Physics and 10P Publishing Limited 2006. Figure 3.26.

In addition, a number of figures were obtained courtesy of individuals as indicated in captions and borrowed from archives of the authors. These include Figs. 6.19, 7.6, 7.8, 9.11, 9.21, 9.22.

1 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.

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

Quantity	Symbol, equation	Value or conversion formula
Avogadro's number	N_A	6.0221×10^{23}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	$\mathrm{d}N/\mathrm{d}t$	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.

2
Noble Fluids as Detector Media

Properties of noble fluids from the point of view of their ability to absorb radiation and transform the absorbed energy into charge carriers or/and photon emission are described in this chapter.

2.1
Physical Properties of Dense Noble Gases

Noble gases have several advantages that make them very attractive as detection media for ionization detectors. First of all, they are available in large amounts as byproducts of the oxygen production for the steel industry. Argon is the third most abundant gas in the atmosphere following nitrogen and oxygen. The world production of xenon is about 27 tons per year. The second, noble gases can be relatively easy purified. For detection of penetration radiation, the most popular are heavy noble gases: argon (Ar), krypton (Kr) and xenon (Xe) because of their inherent high stopping power. Physical properties of noble gases are represented in Table 2.1 and Figs. 2.1 and 2.2. Excellent reviews of the properties of noble gases are available in monographs [16,17] and particular physical data can be found at the "Gas Data" page of Air Liquide website (http://www.airliquide.com). The specific properties of noble gases and their importance for noble gas detectors are discussed below.

Solid noble gases have relatively high density achieving 4 $\text{g}\,\text{cm}^{-3}$ for solid xenon at cryogenic temperatures (Fig. 2.1). However, in the vicinity of the triple point the noble solids are mechanically very soft. For example, one of the authors observed the drift of charged macroscopic ($\sim$ 0.1-mm diameter) gas bubbles through the solid xenon near its triple point with velocity of $\sim$ 1 cm per hour in the laboratory of Obodovsky in 1975. This kind of soft crystal built up due to the weak van der Waals force is sometimes referred to as molecular crystals. The molecular structure is specific for condensed noble gases as well as for oxygen, nitrogen, methane, and for saturated hydrocarbon solids. In molecular crystals, molecules (atoms) can easily change their orientations, which explains the fact that the noble gas solids have dielectric constant larger than that of liquids. Since noble atoms are relatively mobile

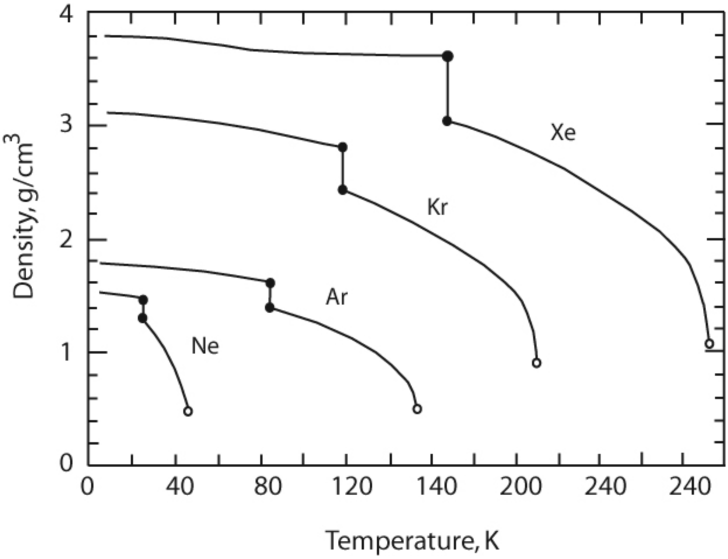

Fig. 2.1 Density of condensed noble gases dependence on temperature (open circles mark critical points, closed circles mark triple points). Redrawn from [18].

in their crystal lattice, the luminescence spectra of the condensed phases and dense gases are similar (see Chapter 4). Noble gases crystallize in the face-centered cubic (fcc) lattice at normal pressure. However, at high pressures and temperatures there is a possibility of phase transitions to body-centered cubic (bcc) structure in solid xenon without changing the volume [19]. Some molecular crystals such as methane perform fcc-bcc transitions at temperatures below the triple point.

The microstructure of the free surface of condensed noble gases is often described as a continuous transition of the gas through the critical point [20]. The average width of the transition is about 2 to 3 times the intermolecular distance. Diffraction investigations of thin samples of crystal xenon confirmed that the 5-nm thick surface layer is structureless having a distance between atoms that was larger than that found in the bulk crystal.

Xenon is a highly compressible, deviating significantly from the ideal gas at densities exceeding 0.2 g cm^{-3} (3 MPa pressure at 300 K). The density of xenon gas can reach $\sim$ 1.5–1.8 g cm^{-3} at comparably low pressures (6–7 MPa). The extremely high solubility of xenon in water which exceeds, for example, the solubility of nitrogen implies that trace amounts of water impurities are difficult to remove from xenon. Indeed, recent chromatographic analysis of highly purified xenon confirmed that water is the dominant impurity limiting performance of liquid xenon scintillation detectors [21].

Tab. 2.1 Physical properties of noble gases.

	He	Ne	Ar	Kr	Xe
Mol. mass μ, g mol^{-1}	4.0026	20.183	39.948	83.80	131.3
Boil. point at 1 atm T_S, K		27.102	87.26	119.74	169
Liq. dens. ρ_S at T_S, kg m^{-3}	0.13(4.2)	1204	1399	2413	3100
Gas dens. (273 K, 1 atm), kg m^{-3}	0.17850	0.8881	1.7606	3.696	5.8971
Latent heat of vaporiz.					
l_S at T_S, J kg^{-1}	20.3	87.20	163.2	107.7	96.29
Latent heat of fusion					
l_T at T_T, kJ kg^{-1}		16.60	29.44	19.52	17.48
Min. energy					
of liquefaction A, kJ kg^{-1}		1376	480	2	2
Debye temp. θ_D, K (T)		64 (<20)	80(<10)	63(<10)	64 (0)
Triple point:	None				
Temperature T_T, K		24.559	83.78	115.76	161.31
Vapor density ρ_G, kg m^{-3}		5	4.05	6.2	12
Liquid density ρ_L, kg m^{-3}		1200	1400	2450	3100
Solid density ρ_S, kg m^{-3}		1442	1622	2830	3640
Pressure p_T, 10^{-2} MPa		4.34	6.876	7.34	8
Liq. surf. tension σ_L, mN m^{-1} (T)		5.54 (T_T)	13.33 (84)	16.31 (116)	18.74 (162)
Critical point:					
Temperature T_C, K	5.25	44.39	150.86	209.38	289.74
Density ρ_C, kg m^{-3}	69.64	483.5	530.8	908.5	1155
Pressure p_C, MPa	0.226	2.686	4.898	5.427	5.764
Mol. vol. V_C, cm^3 mol^{-1}		41.7	75.2	92.2	119.5
Heat cap. c_P, kJ kg^{-1} K^{-1}:					
Gas at 273 K & 1 atm	5.193 (298)	1.030	0.521	0.248	0.158 (298K)
Vapor at T_S		1.030	0.521	0.248	
Liquid at T_S	2.47 (3)	1.84	1.05	0.538	
Solid at T_T	1.087(1)	1.302	0.833	0.428	
Viscosity η, 10^{-7} kg m^{-1} s^{-1}:					
Gas at 273 K & 1 atm	196.14 (293)	296.2	209.8	233	211
Gas at T_K		74.8	123.1	182.0	
Vapor at T_S		46	73		
Liquid at T_S		1240	2760	1600	
Therm. conduct. λ, mW m^{-1} K^{-1}:					
Gas at 273 K & 1 atm	142.64	46.1	16.4	8.78	5.192
Gas at T_K			10.1		
Vapor at T_S			6.5		
Liquid at T_S	0.016(3)	113	125	90	71
Refractive index					
at 293 K & 1 atm, n_D	1.000035	1.000067	1.000284	1.000427	1.000702
liquid at T_T for (λ_{sc}, nm)		1.233(80)			1.566(180)

Tab. 2.1 Physical properties of noble gases. (Continued)

	He	Ne	Ar	Kr	Xe
Diel. constant ε:					
Gas at 273 K & 1 atm	1.000127	1.000554	1.00076	1.000768 (298)	
Vapor at T_S	1.00129	1.00175			
Liquid at (T)	1.19(25)	1.59 (87)	1.63(129)	1.93(164)	
Solid at 20 K	1.230	1.67	1.80	2.23	
Isotherm. compressibility χ_T at T_S, 10^{-9}m^2 N^{-1}		1.92	1.53	1.1	
Solubility in water at n.p. (T, °C), vol/vol	0.0089(20)	0.014(0)	0.0537 (0)	0.099(0)	0.203(0)
Concentr. in air, vol ppm		18	9340	1.14	0.09

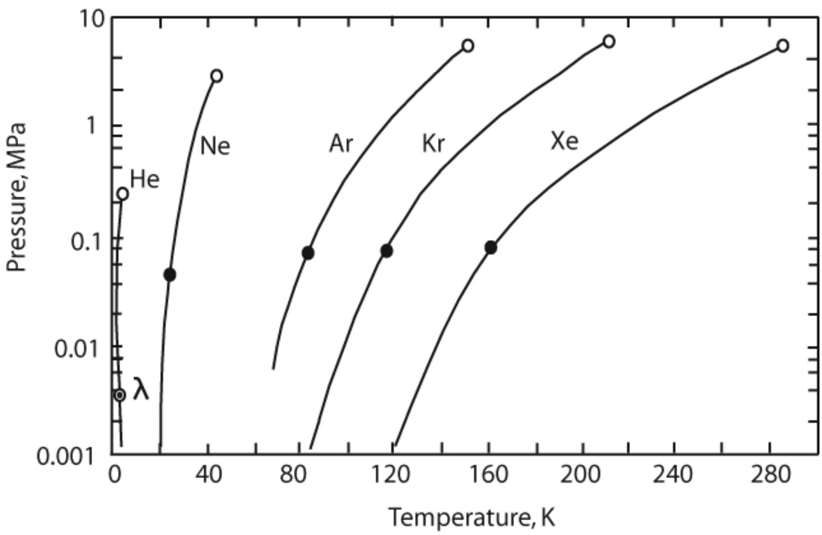

Fig. 2.2 Vapor pressure dependence on temperature of condensed phases of noble gases (open circles mark critical points, closed circles mark triple points, double circle marks lambda point of liquid helium). Redrawn from [18].

2.2
Energy Dissipation in Noble Gases

The most important characteristic of the detecting medium is its ability to stop and absorb nuclear radiation. This ability is characterized by the particle's absorption cross section. Interactions of radiation with noble atoms depend on the nature of the ionizing particles. Charged particles such as electrons or positively charged nuclei (protons, alpha particles, etc.) interact with matter via electrostatic forces. They ionize and excite atoms leaving behind the tracks of positively charged ions and free electrons. Rapidly moving particles also generate bremsstrahlung radiation while passing through matter. If X-rays and gamma rays interact with matter they generate energetic electrons via three primary processes: photoelectric absorption, Compton scattering, and pair production with interaction probabilities that are proportional to $Z^5/E_\gamma^{7/2}$, Z/E_γ and $Z^2\ln(2E_\gamma)$, respectively. Considering its high atomic number ($Z = 54$), Xe is an excellent candidate for a detection medium, especially in the energy range where photoelectric absorption is the dominant process.

The energy of an energetic particle is transferred to the atoms in two ways: ionization and excitation. During the ionization process, an electron is removed from an atom resulting in the formation of a positively charged ion and an electron (an electron–ion pair). The excitation process raises an electron to a higher energy state; it subsequently returns to its original state via a cascade process resulting in the emission of photons having characteristic energies. The secondary electrons from the ionization process may have sufficient kinetic energy to generate more electron–ion pairs or excitations. To understand this process schematically, consider an ionization particle R, which generates electron–ion (holes in solids) pairs e and A^+, and excited atomic states, A^*, as follows:

$$\begin{aligned} R + A &\longrightarrow e + A^+ + R' \\ R + A &\longrightarrow A^* + R' \\ e + A^+ &\longrightarrow A^* \end{aligned} \tag{2.1}$$

The excitation energy released during these processes is manifested in the emission of a VUV photon (radiative process)

$$A^* \longrightarrow A + h\nu_{\mathrm{a}} \tag{2.2}$$

or through the production of heat (nonradiative energy relaxation). In collisions with other atoms, the excitation energy can be released to form an electron–ion pair. In pure gases at low pressures, the characteristic photons, $h\nu_{\mathrm{a}}$, may escape from the gas volume. If the pressure (density) of the gas increases the probability of the absorption of the characteristic photons rapidly increases. As a result, these photons become "trapped" in the volume at a pressure of $\sim 10^3$–10^4 Pa. In dense noble gases ($n \sim 10^{19}$ cm^{-3}), a probability of triple collisions is increased and it takes 10^{-11}–10^{-12} s to produce excited molecules in the reaction of

$$A^* + 2A \longrightarrow A_2^* + A \tag{2.3}$$

Tab. 2.2 Parameters of the energy balance equation for condensed heavy noble gases [23].

	$<E_i>$, eV	N_{ex}/N_i, eV	$<E_{ex}>$, eV	ξ_{se}, eV
Ar	15.4	0.21	12.7	5.15
Kr	13	0.08	10.5	5.50
Xe	10.5	0.06	8.4	4.45

Radiative decay of the excited states leads to the generation of a new population in the emission spectra, so-called molecular continuum

$$A_2^* \longrightarrow 2A + h\nu_m \tag{2.4}$$

Photons emitted at radiative decays of excited atoms $h\nu_a$ diffuse in the dense media and eventually become absorbed by walls and electrodes. However, dense noble gases and their liquid and solid phases are practically transparent for photons $h\nu_m$ from the molecular continuum; such photons can propagate far enough to be used for detection purposes (see Chapter 4).

In general, energy E deposited in the media is distributed between atoms (ions), $<\eta>$, and electrons liberated from neutral atoms, $<\nu>$

$$E =< \eta > + < \nu > \tag{2.5}$$

In case of light particle interactions such as electrons and photons, $E = <\nu>$, and the part of energy loss due to inelastic interaction with atomic electrons can be expressed via Platzman's [22] equation

$$< \nu > (E) = N_i < E_i > +N_{ex} < E_{ex} > +N_i < \xi_{se} > \tag{2.6}$$

where N_i is the number of electron–ion pairs ultimately produced with an average energy expenditure $<E_i>$, N_{ex} is the number of atoms excited at an average energy expenditure $<E_{ex}>$, and $<\xi_{se}>$ is the average kinetic energy of subexcitation electrons, whose energy is lower than the excitation potential and eventually goes into heat.

Parameters of Eq. (2.6) for different aggregate states of the most popular noble gases used as detector media are presented in Table 2.2.

2.3 Ionization Clusters and Principal Limitations on Position Resolution of Noble Gas Detectors

After many interactions the energetic particles eventually slowdown and become thermalized at some distances from the origin. The distance traveled by a charged particle (ranges) in condensed media depends on its charge, mass,