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Resource Letter PD-1 on Particle Detectors

W. PETER TROWER

Physics Department, Virginia Polytechnic Institute, Blacksburg, Virginia 24061

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This is one of a series of Resource Letters on various topics, intended to guide college physicists to literature and other teaching aids that may help them improve course content in specified fields of physics. No Resource Letter is meant to be exhaustive and complete. In time, there may be more than one letter on some of the main subjects of interest. Comments and suggestions concerning the content and arrangement of letters as well as suggestions for future topics will be welcomed and should be addressed to Professor Joel E. Gordon, Chairman, AAPT Committee on Resource Letters, Department of Physics, Amherst College, Amherst, Mass. 01002.

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I. INTRODUCTION

Only by detecting nuclear and subnuclear particles (henceforth abbreviated as particles) can we learn about their intrinsic properties and their mutual interactions. Collecting and codifying these observations will hopefully lead to our understanding of the force responsible for nuclear structure and the role of these particles themselves. A casual perusal of the Nobel awards in physics demonstrates the high regard in which the investion and development of particle detectors has been held. With the advent of each new detector, whole new areas of phenomena have become accessible to study. The prospecting of these newly opened fields has been rewarding in both the variety and significance of the discoveries they have held.

Particles are very small in size ($\sim 10^{-13}$ cm in diameter), possess at most a very small charge ($\sim 10^{-19}$ C), and have a very small mass ($\sim 10^{-27}$ kg). It is remarkable that objects with these minute dimensions can be detected, let alone have their mass, density, size, momentum, etc., measured, in some cases to a few parts in many thousands. This accomplishment is even more impressive when contrasted with the fact that no detector exists which is capable of measuring these same quantities for vastly more sizable objects, such as sand grains in a sandstorm. The property of particles which allows both their detection and the accurate measurement of many of their physical properties is that they possess, or can be converted to other particles which possess, electric charge. This electric charge, our ability to build electric and magnetic devices with which particles can interact, and our thorough understanding of the electromagnetic interaction allow us our fortuitous grasp of the miniature.

Thus, in order to be detected a particle must effect either an electrical signal (e.g., the pulse from a scintillation counter) or an electrically induced signature (e.g., the track left in a bubble chamber). Whether signal or signature, its distinct characteristics, either spatial or temporal, must be associated uniquely with the particle under study. Standard devices are linked together to form a processing stream for the purpose of manipulating these data. The end result is always a physical measurement of a property of a particle. The place in the processing stream where the "detector" leaves off is, of course, arbitrary. We choose to define a detector rather restrictively as the actual physical material with which the particle interacts, and in the case of chambers, the apparatus which encloses it. Accordingly, only the physical processes governing the interaction specific to a device are discussed and directly referenced. This will provide insufficient information to allow for the construction of a workable detector, for much attendant apparatus, both mechanical and electrical (hardware) as well as computational (software), is required to transmute these physical phenomena into viable experimental tools. The despairing reader should be consoled by the knowledge that an effort has been made to assure that sufficient technological counsel to effect construction is available in the references contained in the bibliography.

We have severely limited the number of entries in this bibliography, as the literature related to particle detectors is indeed immense. Reasonable availability was requisite for inclusion, and thus, recent publications appear here at the expense of earlier works of the same quality. The grading of references for a bibliography on a theoretical subject is easily made by judging the level of mathematical sophistication: E, elementary, I, intermediate, and A, advanced. A similar criterion applied to a basically experimental bibliography such as this would result in a ranking by successively greater preoccupation with the details (usually engineering) of each device. This being contrary to the spirit of the Resource Letters, we assign highest ranking to the most comprehensive and best documented articles. Finally, we include the reports of discoveries which were directly related to the award of a Nobel Prize. These have been marked by an asterisk (*) to denote their introductory nature with respect to subject if not always exposition.

Useful discussions with Dr. F. Turkot, Professor J. R. Ficenec, and Professor D. S. Wollan during the preparation of this bibliography are gratefully acknowledged.

II. INTERACTIONS OF PARTICLES WITH MATTER

The basis of operation of any particle detector is the interaction the particle makes with the material in the detector's sensitive volume. This interaction in turn depends on the properties of the particle (e.g., mass, charge, energy, stability against decay) and the physical and chemical properties of the detecting medium. Thus a discussion of the physical process by which a particle may interact with matter necessarily precedes an enumeration of specific detectors.

1.I "Passage of Radiation Through Matter." P. Marmier and E. Sheldon in *Physics of Nuclei and Particles.* (Academic Press Inc., New York, 1969), Vol. 1, p. 97. A good section of an excellent textbook.

2.A "Interaction of Radiation with Matter." R. M. Sternheimer in *Methods of Experimental Physics,* L. C. L. Yuan and C-S Wu, Eds. (Academic Press Inc., New York, 1961), Vol. 5A, p. 1. A detailed general discussion with extensive references to experimental verification.

A. Charged Particles

Particles lose energy by collision with either of the two constituents of an atom—nuclei or electrons. The greater the probability and uniqueness of a particular collision occurring, the more likely the process is to be useful as the basis of a particle detector. Regardless of the process, the end result must be electrons or ions which can constitute an electrical signal or electrically induced signature suitable for subsequent manipulation.

When a charged particle intrudes into the electric field of a nucleus, it is deflected and thus accelerated. An accelerated charge radiates part of its energy in the form of photons by a process called bremsstrahlung. The energy lost per unit length by bremsstrahlung varies as the square of nuclear charge and inversely with particle mass. Further, the scattering can be inelastic, leaving the nucleus to de-excite by the emission of photons or charged particles. However, none of these nuclear processes contributes significantly to the total energy loss of a charged particle in matter.

It is the collision of charged particles with atoms through which most of the particle energy loss occurs and is the process on which most detectors are based. The consequences of charged particle–atom collisions are basically two. In the first, the scattering excites the atomic electron cloud which, when it returns to the ground state, usually does so by emitting photons. In the second, an individual electron will be ejected directly in the scattering process, leaving the atom ionized. The ejected electrons, called delta rays, can also produce ions if sufficiently energetic. The ion trail formed along the path of a charged particle is widely utilized in detectors. The energy required to form an individual ion–electron pair is almost independent of the nature and energy of the particle and nature of the medium. The total energy deposited in a given length of particle path, which is proportional to the probability for ionization to occur, varies roughly with the square of the charge of both the particle and the atomic nucleus of the medium, the density of the medium, and with the inverse square of the particle's kinetic energy.

3.E **"High Energy Particle Data, Volume II, Range-Energy and dE/dx Plots of Charged Particles in Matter."** W. P. Trower (1966 rev.) and **"High Energy Particle Data, Volume IV, Range-Momentum and dP/dx Plots of Charged Particles in Matter."** W. P. Trower (1966 ed.). University of California Radiation Laboratory Report UCRL 2426. Graphical presentation of particle range and differential energy or momentum loss in various elements constitutes the two sets of tables.

4.E **"Tables of Energy Losses and Ranges of Electrons and Positrons."** M. J. Berger and S. M. Seltzer. National Aeronautics and Space Administration Report, NASA SP-3012 and SP-3036. Tabular presentation of range and differential energy loss in various elements and compounds appear here.

5.E **"Tables of Energy Losses and Ranges of Heavy Charged Particles."** W. H. Barkas and M. J. Berger. National Aeronautics and Space Administration Report, NASA SP-3013. Tabular presentation of range and differential energy loss in various elements and compounds appear here.

6.I **"Collisions between Charged Particles, Energy Loss and Scattering."** J. D. Jackson in *Classical Electrodynamics*. (John Wiley & Sons, New York, 1962), Chap. 13. An excellent discussion of the electrodynamics in energy loss processes.

7.I **"Penetration of Atomic Particles through Matter."** N. Bohr, Kgl. Danske Videnskab. Selskab Mat-fys. Medd. **18,** No. 8 (1948). The result of a lifetime interest in this subject by one of the giants of twentieth century physics.

8.I **"Passage of Radiations through Matter."** H. A. Bethe and J. Ashkin in *Experimental Nuclear Physics*, E. Segré, Ed. (John Wiley & Sons, New York, 1953), Vol. 1, p. 166. A beautiful exposition of these physical processes.

9.A **"Penetration of Protons, Alpha Particles, and Mesons."** U. Fano in *Annual Reviews of Nuclear Sciences*, E. Segré, Ed. (Annual Reviews, Inc., Palo Alto, California, 1963), Vol. 13, p. 1. A state of the art reviews which discuss energy loss of "intermediate" ions in their passage through matter. Consideration is taken of the exact atomic structure of the medium.

10.A **"Passage of Heavy Ions Through Matter."** L. C. Northcliffe in *Annual Reviews of Nuclear Science*, E. Segré, Ed. (Annual Reviews, Inc., Palo Alto, California, 1963), Vol. 13, p. 67. Complements the previous article by discussing the multiply ionized particle and its reacquired neutrality as it slows down in matter.

B. Photons

We only consider the detection of those photons which originate in nuclear and atomic de-excitations. These photons have three characteristic interactions with matter, all of which result in charged particles and thus allow for their detection.

A photon can be absorbed by an electron ejected from an atom in a process called the photoelectric effect. The more tightly bound the electron, the more likely it is to be ejected. The probability of the photoelectric effect occurring varies with about the fifth power of the atomic charge and in a complicated manner with photon energy (roughly as the inverse third power near 100 keV, to the inverse first power above $\frac{1}{2}$ MeV). The resulting electron vacancy is filled by the rearrangement of less tightly bound members of the electronic constellation. In this process photons are usually emitted, although occasionally a loosely bound electron is ejected (Auger effect).

A photon can elastically scatter from an individual atomic electron, in a process known as the Compton effect. Here the change of the wavelength (energy) and direction (momentum) of the incident photon are uniquely related to the motion of the dislodged electron. The average angle at which the photon tends to be scattered decreases with increasing incident photon energy.

The probability of Compton scattering occurring is complicated, but depends in part on the number of electrons in the target material (i.e., on the density of material and on nuclear charge).

A third process called photon materialization occurs if a photon has more energy than that required to produce a particle–antiparticle pair. For example, a photon of at least 1 MeV is needed to produce an electron–positron pair. If a photon passes near enough to either an atomic electron or nucleus to be able to transfer energy and momentum to it, then photon materialization is possible. The probability of such a process occurring depends roughly on the second power of the charge of the assisting particle. Thus, pair creation will occur more often in the field of a nucleus (pair production) than in the field of an electron (triplet production). Furthermore, the antiparticle produced in the process annihilates upon contact with matter of its complementary kind. In the case of positrons, this results in two or occasionally three photons.

*11.E **"Über einen die Ereugung und Verwandlung des Lichtes betreffenden heuristischen Gersichtspunkt."** A. Einstein, Ann. Physik **17**, 132 (1905). Nobel Prize in Physics. The citation for the 1921 award reads "for his service to theoretical physics and especially for his discovery of the law of the photoelectric effect."

*12.E **"X-rays as a Branch of Optics."** A. H. Compton in *Nobel Lectures Physics 1922–41* (Elsevier Publ. Co., New York, 1965), p. 174. The citation for the 1927 award reads "for his discovery of the effect named after him."

13.I **"The Interaction of Gamma Rays with Matter."** W. F. Hornyak in *Nuclear Spectroscopy*. F. Ajzenberg-Selove, Ed. (Academic Press Inc., New York, 1960), Pt. A, p. 211. Besides a discussion of electromagnetic interactions with matter, it deals with the application of these interactions to the determination of nuclear structure information.

14.I **"Interaction of γ-Radiation with Matter."** C. M. Davisson in *Alpha-, Beta-, and Gamma-Ray Spectroscopy.* K. Siegbahn, Ed. (North-Holland Publ. Co., Amsterdam, Netherlands, 1965), Vol. 1, p. 37. Like the previous reference except the adjective encyclopedic appropriately applies.

15.I **"The Interaction of Electromagnetic Radiation with Matter."** R. D. Evans in *The Atomic Nucleus* (McGraw-Hill Book Co., New York, 1955), p. 672. A discussion of the process usefully accented for the experimentally inclined.

16.A **"Interactions of Photons and Leptons with Matter."** R. R. Roy and R. D. Reed. (Academic Press Inc., New York, 1968). A detailed, well written account of the leptonic and electromagnetic interactions of elementary particles with matter.

C. Other Neutral Particles

Other neutral particles also depend for their detection upon a reaction whose products are charged and thus detectable. There are basically two types of these reactions. If the neutral particle is unstable (i.e., can spontaneously disintegrate) and has a short lifetime relative to its transmit time in the detector, then its detection can be based on the uniqueness of its charged and photon products.

Alternatively, the electrical neutrality of the particle may permit it to approach close enough to a charged nucleus to effect a strong interaction. This may result in the nucleus recoiling (elastic scattering), the production of various particles, some charged (transmutation reaction), an amalgamation which then breaks into two parts (fission reaction), or a capture from which a photon or electron eventually appears (activation reaction).

17.I **"The Interaction of Neutrons with Matter."** W. Selove in *Nuclear Spectroscopy*, F. Ajzenberg-Selove, Ed. (Academic Press Inc., New York, 1960), p. 335. A simple introduction to neutron interactions.

18.I **"Detection of Neutrons."** L. F. Curtiss in *Introduction to Neutron Physics* (D. Van Nostrand Co., Inc., New York, 1959), Chap. 4. A general description of various neutron detectors.

19.I **Neutron Detection.** W. D. Allen (Philosophical Library, Inc., New York, 1960). Of assistance to the experimentalist in measuring neutrons.

20.A **Fast Neutron Physics.** J. B. Marion and J. L. Fowler, Eds. (Interscience Publishers, New York, 1960), Vol. 1. An encyclopedia treatment of neutron interaction and detection.

21.A **"The Neutron."** B. T. Feld in *Experimental Nuclear Physics*, E. Segré, Ed. (John Wiley & Sons, New York, 1953), Vol. 2, p. 209. Although somewhat dated this is still an excellent description of the neutron and its interaction with matter.

III. INDIVIDUAL PARTICLE DETECTORS

We now deal with the devices which employ the physical principles discussed above. We confine our attention to those detectors which establish the existence of distinct individual particles. Detectors which only determine the sizes of particle aggregations (e.g., electroscopes, changes in chemical properties, etc.) are not discussed, even though some individual particle detectors can also be used for this purpose (e.g., photographic emulsion, ion chambers, etc.). If a detector, aside from establishing the existence of a particle, also measures other properties (e.g., gamma-ray pulse height in sodium iodide is also proportional to its energy), this fact is noted. Arrays of detectors whose purpose it is to measure specific physical properties of the particle (e.g., spectrometers, hodoscopes, etc.) are not dealt with. Some general references which discuss a great many of these detectors are:

22.E "Charged-Particle Detectors." N. S. Wall in *Nuclear Spectroscopy*, F. Ajzenberg-Selove, Ed. (Academic Press Inc., New York, 1960), Pt. A, p. 31.

23.E Nuclei and Particles. E. Segré (W. A. Benjamin Inc., New York, 1964), Chap. 3.

24.I Nuclear Physics. L. C. L. Yuan and C. S. Wu, Eds. (Academic Press Inc., New York, 1961), Pt. A.

25.I Techniques of High Energy Physics. D. Ritson, Ed. (Interscience Publishers, Inc., New York, 1961).

26.I Nuclear Radiation Detection. W. J. Price (McGraw-Hill Book Co., New York, 1968), 2nd ed.

27.I Experiments in Modern Physics. A. C. Melissinos (Academic Press Inc., New York, 1966).

Individual particle detectors can be classified by the permanence of the record they make in the detection process.

A. Static Detectors

A static detector creates a permanent record of the ion trail caused by the passage of a charged particle. Although there are only two types of static detectors, they are useful because, in addition to permanence, they have the quality that a particle track can be located with high precision. These detectors also require no supporting equipment for their exposure and can be made arbitrarily small so that they can be used in applications which are inaccessible for larger instrumental setups (i.e., space craft).

1. Photographic Emissions

In 1896 Becquerel accidentally recorded the first nuclear radiation, when he placed some radioactive material in contact with a photographic plate, which resulted in its exposure. When a charged particle passed through the emulsion, it irreversibly rearranged the molecular bonds (i.e., "developed" the plate) along the particle's path. The newly formed molecules when "fixed" absorbed much of the light which shines on them and thus appear black along the length of a particle's track. If a particle comes to rest in the emulsion, then the length of its track (i.e., range) is a measure of its entrance energy, and thereby its mass if its charge is known. At velocities low with respect to that of light, the density of the black grains along the particle's track is proportional to its specific energy loss and can provide a measure of its velocity. For velocities near the speed of light, the magnitude of the deviation of a particle track from a straight line is a measure of its velocity. This deviation, called multiple scattering, is caused by a series of successive small coulomb deflections and depends inversely on the particle velocity and momentum and directly on the average nuclear charge of the detector material. The energy distribution of delta rays further serves to specify a particle's energy.

***28.E "The Cosmic Radiation."** C. F. Powell in *Nobel Lecture Physics, 1942–62* (Elsevier Publ. Co., New York, 1964), p. 137. The citation for the 1950 award reads "for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method."

29.E "The Tracks of Nuclear Particles." H. Yagoda, Sci. American **194**, 40 (May 1956). A popular introduction.

30.E "Resource Letter NPE-1 on Nuclear Photographic Emulsions." M. W. Friedlander, Amer. J. Phys. **35**, 1105 (1967). Provides a nice introduction to the subject with a good bibliography.

31.I The Study of Elementary Particles by the Photographic Method. C. F. Powell, P. H. Fowler, and D. H. Perkins (Pergamon Press, Ltd., London, 1959). A picture book of emulsion studies with a narrative.

32.A "Nuclear Emulsions." M. M. Shapiro in *Handbuch der Physik*, S. Flügge, Ed. (Springer-Verlag, Berlin, 1958), Vol. 45, p. 342. An excellent survey.

33.A Nuclear Research Emulsions. W. H. Barkas (Academic Press Inc., New York, Vol. I, 1963; Vol. II in preparation). An encyclopedic work which definitively covers the field.

2. Dielectric Solids

It has been recently discovered that virtually all insulating solids are capable of registering and retaining indefinitely the ion trail left by the passage of a charged particle. In order to read the particle tracks, an irradiated dielectric must be developed and fixed (i.e., etched) with some acid appropriate to the solid. Hydrofluoric and phosphoric acids are commonly used for this purpose. Since the solid material left along the ion trail is more reactive than the unexposed portion, a hollow tube on the order of a micron in length will result from this treatment. Visible light will scatter from this tube so that the dimension of the tube can be determined by viewing the material with a microscope. The length of the etched tube depends directly on the charge of the penetrating particle. This detector appears to have greater application in historical dating than in the investigation of particle properties.

34.E "Nuclear Tracks in Solids." R. L. FLEISCHER, P. B. PRICE, AND R. M. WALKER, Sci. American **220**, 30 (June 1969). A popular article by those who have been the most active in advancing the technique.

35.A "Solid-State Track Detectors: Applications to Nuclear Science and Geophysics." R. L. FLEISCHER, P. B. PRICE, AND R. M. WALKER, in *Annual Reviews of Nuclear Science*, E. Segré, Ed. (Annual Reviews, Inc., Palo Alto, California, 1965), Vol. 15, p. 1. A review of the field.

B. Dynamic Detectors

By far the most numerous and useful class of particle detectors are the dynamic detectors whose impression of the passage of a particle is fleeting. For an event's proper recording, some permanent ancillary device (i.e., scaler, photograph, magnetic tape, etc.) must be employed.

1. *Counters*

We define a counter to be a device which produces a signal upon the passage of a particle. Information from this signal is contained in its size, shape, and temporal order of appearance relative to signals from other counters. Counters can be classified by the physical character of the primary signal they produce.

A. ELECTRICAL

The electrical counter produces an electrical signal directly from the ion trail which a particle creates in the detector medium. The physical state of the medium further categorizes these detectors.

1. Gas (*Transport*). A sealed, gas-filled vessel containing a pair of electrodes across which a voltage is maintained is the basic transport counter. When a charged particle passes between the electrodes, its associated ions will dissociate, each being attracted to the electrode of its complementary charge. As the ion pairs separate, they induce image charges on the electrodes which can be detected externally. The details of the subsequent movement or transport of these ions are very complex. These counters can be characterized by the behavior of this transport phenomenon for different ranges of operating voltages.

(A.) IONIZATION "CHAMBER" MODE. This operational mode uses low voltages and any gas which does not have a large affinity for electron attachment. Only those ion pairs formed by the original particle are collected.

36.I Ionization Chambers and Counters. B. ROSSI AND H. STAUB (McGraw–Hill Book Co., New York, 1949). An ancient but excellent reference on a subject which hasn't experienced much activity in the past generation.

37.I "Pulsed Ionization Chambers and Proportional Counters." W. FRANZEN AND L. W. COCHRAN in *Nuclear Instruments and Their Uses*, A. H. Snell, Ed. (John Wiley & Sons, New York, 1962), p. 3. A broad review of the subject.

38.A "Ionization Chambers in Nuclear Physics." H. W. FULBRIGHT in *Handbuch der Physik*, S. Flügge, Ed. (Springer-Verlag, Berlin, 1958), Vol. 45, p. 1. An excellent review.

(B.) PROPORTIONAL COUNTER MODE. The proportional counter mode uses higher operating voltages. This increased potential accelerates the electrons and ions sufficiently so that their collision with neutral gas molecules can produce more electrons and ions. Thus a multiplication of ions results whose magnitude is proportional, over certain ranges of operating voltages, to the original number of ion pairs produced.

39.I "Proportional Counters and Pulse Ion Chambers." S. C. CURRAN AND H. W. WILSON in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, K. Siegbahn, Ed. (North-Holland Publ. Co. Amsterdam, Netherlands 1965), Vol. **1**, p. 303. A recent review of the devices and techniques.

40.A "The Proportional Counter as Detector and Spectrometer." S. C. CURRAN in *Handbuch der Physik*, S. Flügge, Ed. (Springer-Verlag, Berlin, 1958), Vol. 45, p. 174. A comprehensive review article.

(C.) GEIGER COUNTER MODE. At quite large operating voltages, the electron avalanche process creates a great number of photons, with both visible and ultraviolet wavelengths, most of which are absorbed in the gas or escape the container. However, some of them eject photoelectrons from the walls of the container. These photoelectrons are then accelerated towards the anode and produce showers. This process quickly causes a discharge in the entire volume of the counter. Thus an initial ion pair is sufficient to produce a discharge whose magnitude is independent of ion density.

*41.E "The Coincidence Method." W. Bothe in *Nobel Lectures Physics 1942–62* (Elsevier Publ. Co., New York, 1964), p. 268. The citation for the 1954 award reads "for the coincidence method and his discoveries made therewith."

42.A "Geiger Counters." S. A. Korff in *Handbuch der Physik*, S. Flügge, Ed. (Springer-Verlag, Berlin, 1958), Vol. 45, p. 52. A full account of the process and construction of the device.

2. Solid (*Conduction*). A charged particle passing through a crystalline material may elevate loosely bound electrons into the conduction band. If the crystal is pure and an external electrical field is applied, then the electrons and holes will migrate to the electrodes, thus causing an electrical current. The variety of these conduction counters can be enumerated by their conductive properties.

(A.) Insulators. Nonconducting materials, such as sulfur, diamond, and zinc and cadmium sulfides at room temperature, and silver and thallium chloride at liquid nitrogen temperature, are used in conduction counters. Polarization effects caused by prolonged irradiation and the subsequent accumulation of trapped charges as well as the nonuniform spatial distribution of traps in the crystal unfortunately lead to a highly uncertain energy-to-pulse-height relationship. Therefore, insulating conduction counters are very little used.

(B.) Semiconductors. If a very highly purified semiconductor of the *pn* type, like silicon at room temperature or germanium at liquid nitrogen temperature, is subjected to an electric field, it will produce a pulse when an ionizing particle traverses the junction. This pulse is very fast, on the order of 10 nsec, and has an amplitude proportional to the energy lost by the particle in the junction layer. Since only about 3 eV are required to produce an ion pair in a semiconductor, compared with 30 eV in a gas, more ion pairs are produced, and thus excellent energy resolution results. A severe limitation on the usefulness of these devices is their present small size.

43.I "Semiconductor Spectrometers." G. T. Ewan in *Progress in Nuclear Techniques and Instrumentation*, F. J. M. Farley, Ed. (North-Holland Publ. Co., Amsterdam, Netherlands, 1968), Vol. 3, p. 69. A good discussion of silicon and germanium devices and their use.

44.I Semiconductors Counters for Nuclear Radiations. G. Dearnaley and D. C. Northrop (Spon, London, 1966), 2nd ed. A readable discussion of the subject of semiconductors as counters.

45.I Semiconductor Particle Detectors. J. M. Taylor (Butterworths Scientific Publications, Ltd., London, 1963). A nice development of the subject, but now somewhat out of date.

46.A "Semiconductor Nuclear Radiation Detectors." A. J. Tavendale in *Annual Reviews of Nuclear Science*, E. Segré, Ed. (Annual Reviews, Inc., Palo Alto, California, 1967), Vol. 17, p. 73. A review which is concise, thorough, and well documented.

B. Optical

In optical counters, photons are produced when ionizing particles pass through the detector material. This light is then transferred, usually by some transparent material, to a photomultiplier tube, the purpose of which is to convert the light into an electrical signal whose amplitude is proportional to the number of photons present. The photomultiplier tube is constructed with a series of shaped electrodes maintained at increasing voltages, so that when photons incident on the first stage create photoelectrons, these electrons will be accelerated and directed to the next stage. There these electrons eject additional electrons from that electrode. This cascade multiplication continues until the signal is read out at the last (anode) or next to last (dynode) stage. We classify optical counters by the light producing process which occurs.

47.A Photoelectric Materials and Devices. S. Larach, Ed. (D. Van Nostrand Co., Princeton, N. J., 1965). An extremely valuable compendium of papers on the process responsible for and materials used in photomultipliers.

1. Scintillation Counters. The scintillation counter is used extensively for the measurement of particle energy as well as existence because of its high efficiency, fast response, and linear signal-to-energy relationship. Its operation is dependent upon having a fraction of a charged particle's energy converted into visible or ultraviolet light. Two types of scintillating phosphors are in wide use.

(A.) Inorganic. The excitation of loosely bound valence electrons up into the conduction band of the scintillation material by the passage of a charged particle initiates the scintillation process. De-excitation takes place at imperfections in the crystal lattice by three main mechanisms. In the first, a lattice defect acts as a quenching center where the electron energy is converted into heat. The second is associated with a luminescence center, and de-excitation is accompanied by photons. This fluorescence phenomenon is the basis for the inorganic scintillation detector. A third mechanism allows the trapped electrons to acquire energy from the thermal lattice vibrations and upon de-excitation, return to the conduction band, or drop to the ground state by a radiationless transition. This process, called phosphorescence, accounts for the delayed emission of light and is a hindrance to the operation of a scintillation detector. Commonly used activated inorganic phosphors (impurities are introduced to increase the number of luminescence centers) are zinc sulfide for heavy charged particles, sodium iodide for gamma-ray photons, and lithium iodide for neutrons. The typical decay time is on the order of a microsecond.

(B.) Organic. Organic phosphors rely on the fluorescence property of individual molecules and not on that of a crystal structure. Thus organic scintillators can exist as gases, liquids, and solids. The earliest material used was napthalene, which has now been replaced by anthracene, stilbene, and terphenyl. The desirable qualities of these compounds, besides being easily formable, are their high luminescent efficiency and short luminescent decay time ($\sim$10 nsec).

48.E Nuclear Radiation Detectors. J. Sharpe (Methuen & Co. Ltd., London, 1964), 2nd ed. A well referenced review of particle interactions and scintillation devices.

49.E "Scintillation Counters." G. B. Collins, Sci. American **189,** 36 (November 1953). An old but worthwhile introduction.

50.I Scintillation Counters in High Energy Physics. Yu. K. Akimov (Academic Press Inc., New York, 1965). A readable translation of a Russian monograph on the construction and use of scintillation techniques.

51.I Luminescence and the Scintillation Counter. S. C. Curran (Butterworths Scientific Publications, Ltd., London, 1953). The information in this volume is dated but still provides a good introduction.

52.I Organic Scintillation Detectors. S. Schram (Elsevier Publ. Co., New York, 1963). A short but very useful book which concerns itself chiefly with the material details of the physical process.

53.I Scintillation Spectroscopy of Gamma Radiation. S. M. Shafroth, Ed. (Gordon and Breach, New York, 1967). Emphasis on the applications of the technique.

54.A The Theory and Practice of Scintillation Counting. J. B. Birks (Pergamon Press, Inc., New York, 1964). An encyclopedia about the phenomena and techniques of scintillation counters.

2. Čerenkov Counters. When a charged particle passes through a medium at a velocity greater than the speed of light in that medium, it spontaneously emits light. The cosine of the angle with respect to the particle's direction at which the light is emitted is inversely proportional to the index of refraction of the medium and the velocity of the particle. The intensity of the light varies as the square of the particle's charge and the sine of the angle of emission. This radiation was first observed by Čerenkov and was explained by Frank and Tamm in terms of an optical shock wave. Detectors using this effect are usually of the threshold type, in that they respond only when a particle's velocity exceeds a preset value. In a gas counter this threshold is changed by adjusting the pressure and thereby the density (index of refraction). The counter is very fast since light is produced directly, and the response is only limited by light collection efficiency and transit time.

***55.E "Radiation of Particles Moving at a Velocity Exceeding that of Light and Some of the Possibilities for their Use in Experimental Physics."** P. A. Čerenkov. **"Optics of Light Sources Moving in Refractive Media."** I. M. Frank. **"General Characteristics of Radiations Emitted by Systems Moving with Super-light Velocities with Some Applications to Plasma Physics."** I. E. Tamm in *Nobel Lectures Physics 1942–62* (Elsevier Publ. Co., New York, 1964), p. 421. The citation for the 1958 award reads "for the discovery and the interpretation of the Čerenkov effect."

56.I "Cherenkov Detectors." G. W. Hutchinson in *Progress in Nuclear Physics*, O. R. Frisch, Ed. (Pergamon Press, Inc., New York, 1960), Vol. 8, p. 197. An extensive review article about the theory and technique of Čerenkov detectors.

57.A Čerenkov Radiation and Its Applications. J. V. Jelley (Pergamon Press, Inc., New York, 1958). A somewhat dated but complete account of the Čerenkov effect and devices.

2. *Chambers*

We define a chamber to be a device which allows many data about a physical event to be recorded simultaneously and then be related to each other. We differentiate among chambers, as we did among counters, on the basis of the physical character of the signal or signature each produces.

A. Electrical

The electrical chamber uses the ion trail left in a gas by a charged particle to discharge its electrodes when they are pulsed with an electrical field.

1. Spark Chamber. A charged particle-induced discharge can make itself known in several ways. The sound a spark makes can, if picked up by several precisely located microphones, be used to determine the location of the spark. Cameras can be substituted for microphones and record the light which attends the discharge, yielding greater precision than the acoustical detector. This advantage is compensated for by the labor required to reduce the photographic data to digital information. If the electrodes are made of evenly spaced and precisely located wires, the spark location can be determined from those wires which carried the current of the discharge. There are three ways currently used to read out information from a wire spark chamber. In the first (core readout), the end of each wire is threaded through a small ferrite core. Current passing through the wire will flip (i.e., change the direction of magnetization of) the core. A second way (magnetostrictive readout) is accomplished by passing the end of each wire across a delay line of special composition, which has a longitudinal magnetic orientation. The pulsing of the chamber starts a clock, the current in the wire induces a magnetic shock wave in the delay line, and the spark location can be deduced from the time of detection of the shock wave. A third method (sparkostrictive readout) employs the same principle as the second, except that it relies on a spark to induce the shock wave.

58.E "The Spark Chamber." G. K. O'Neill, Sci. American **207,** 36 (August 1962). An introductory exposition which is clear and well stated.

59.I "The Development of Spark Chamber Techniques." G. Charpak, L. Massonnet and J. Favier in *Progress in Nuclear Techniques and Instrumentation,* F. J. M. Farley, Ed. (North-Holland Publ. Co., Amsterdam, Netherlands, 1965), Vol. 1, p. 321. A nice discussion of the physics and techniques of spark chambers.

60.I "Spark Chambers." W. A. Wenzel in *Annual Reviews of Nuclear Science,* E. Segré, Ed. (Annual Reviews, Inc., Palo Alto, California, 1964), Vol. 14, p. 205. Many technical details of the state of the art are presented, and by necessity it is out of date. Basic ideas are there, however, and extensive references to earlier work are available.

61.A Bubble and Spark Chambers. R. P. Shutt, Ed. (Academic Press Inc., New York, 1967), Vols. 1 and 2. An excellent and timely review.

2. Proportional Wire Chamber. The proportional wire chamber is constructed much like the ordinary wire chamber except that an amplifier is attached to the end of each wire. The signal from each wire is treated individually; thus multiple sparks can be detected from the pulse height and/or length of pulse.

62.I "The Use of Multiwire Proportional Counters to Select and Localize Charged Particles." G. Charpak, R. Bouclier, T. Bressani, J. Favier, and C. Zupancic, Nucl. Inst. Methods **62,** 262 (1968). The first announcement of this very promising technique.

63.I "A Beam Profile Analyser Using Proportional Multiwire Chamber." G. Amato and G. Petrucci, CERN 68-33. Describes an interesting application of these chambers.

3. Streamer Chambers. In the streamer chamber the useful volume is not broken up by the placement of planes as in spark chambers. The streamer chamber, which has a large active region, depends for its operation upon the early termination of the electrical discharge so that the ion trail forms along the path of the particle and does not connect electrodes. In the presence of a magnetic field and for relatively low energy particles, this deviation from a direct route can be considerable indeed. Photographic means are employed to stereorecord each event. The response time of the streamer is such that it can be triggered externally.

64.E "The Streamer Chamber." D. Yount, Sci. American **217,** 38 (October 1967). A popular introduction.

65.I "Stream Chamber Development at SLAC." A. Odian in *Proceedings 1966 International Conference on Instrumentation for High Energy Physics* (USAEC, Washington, D. C., 1966), Conf. 660918, p. 49. A discussion of the early developments in streamer chambers.

B. Nonelectrical

1. Fluid Chambers. If a volume of vapor (liquid) is suddenly compressed (expanded) so that it finds itself in a supersaturated (superheated) condition, it must decide where spatially to begin to relieve its unstable state by condensing (boiling). If, at the moment of decision, a charged particle passes through the fluid, leaving a wake of ions, the equivalence of all parts of the medium is destroyed and droplets (bubbles) form, using these ions as their centers of nucleation. Fluid chambers can be categorized by the physical state of the detection medium.

(A.) VAPOR (CLOUD) CHAMBERS. The observation that condensation of supersaturated vapors in the presence of ions produces droplets which are visible with strong illumination represented the invention of the cloud chamber. Supersaturation is accomplished by compression, and the chamber remains sensitive for about a tenth of a second, which allows it to be triggered. The event is usually then photographed. The remaining ions are swept away after each expansion by an electric field. Operation is possible in a magnetic field, and thus particle momentum can be determined from the curvature of the track once the stereoscopic photographs are analyzed and the spatial track coordinates are determined. Turbulence and multiple scattering limit the accuracy of these measurements. It is possible to build a cloud chamber without a mechanical expansion mechanism by utilizing a vertical temperature gradient (increasing upwards) for its sensitivity. This type of chamber is called a diffusion chamber.

***66.E "On the Cloud Method of Making Visible Ions and the Tracks of Ionizing Particles."** C. T. R. WILSON in *Nobel Lectures Physics 1922–41* (Elsevier Publ. Co., New York, 1965), p. 194. The citation for the 1927 award reads "for his method of making the paths of electrically charged particles visible by condensation of vapor."

***67.E "Cloud Chamber Researches in Nuclear Physics and Cosmic Radiation."** P. M. S. BLACKETT in *Nobel Lectures Physics 1942–62* (Elsevier Publ. Co., New York, 1964), p. 93. The citation for the 1948 award reads "for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation."

68.I Cloud Chamber Photographs of the Cosmic Radiation. G. D. ROCHESTER AND J. G. WILSON (Pergamon Press Ltd., London, 1952). A picture book of typical and unusual cloud chamber pictures with narrative.

69.A "Cloud Chambers." C. M. YORK in *Handbuch der Physik*, S. Flügge, Ed. (Springer–Verlag, Berlin, 1958), Vol. 45, p. 260. A well documented description of the physics and technology of cloud chambers.

(B.) LIQUID (BUBBLE) CHAMBERS. The sudden lowering of the pressure on a liquid below the boiling point in the presence of ions produces bubbles which are visible with strong illumination. After expansion the bubble chamber remains sensitive for only about 10 msec, thus making it very difficult to trigger. The bubbles are squeezed out of existence during the next cycle of the chamber. Many liquids can be used for operational bubble chambers; but hydrogen is the most desirable from the standpoint of the interpretative simplicity of the physics.

***70.E "Elementary Particles and Bubble Chambers."** D. A. GLASER in *Nobel Lectures Physics 1942–62* (Elsevier Publ. Co., New York, 1964), p. 525. The citation for the 1960 award reads "for the invention of the bubble chamber."

***71.E "Recent Developments in Particle Physics."** L. W. ALVAREZ, Science **165**, 1071 (1969), Nobel Lecture in Physics, 1964. The citation for the 1968 award reads "for his decisive contribution to elementary particle physics, in particular the discovery of a large number of resonance states made possible through his development of the technique of using a hydrogen bubble chamber and data analysis."

72.E LRL Detectors: The 72-inch Bubble Chamber. (Lawrence Radiation Laboratory, Berkeley, California, 1960). An interesting elementary introduction to this device.

73.I "The Bubble Chamber." D. V. BUGG in *Progress in Nuclear Physics*, O. R. Frisch, Ed. (Pergamon Press Inc., New York, 1959), Vol. 7, p. 1. An old fashioned but pedagogically instructive account of the whole bubble chamber process from chamber construction to evaluation of measurements.

61.A Bubble and Spark Chambers: Principles and Use. R. P. SHUTT, Ed. (Academic Press Inc., New York, 1967), Vols. 1 and 2. An excellent and timely review.

74.A Bubble Chambers. YU. A. ALEKSANDROV, G. S. VORONOV, V. M. GORDUNKOV, N. B. DELONE, AND YU. I. NECHAYER (Indiana University Press, Bloomington, Ind. 1967). A description of the development and problems of bubble chambers from a Russian point of view.

2. Solid (Luminescent) Chamber. This device directly uses the light produced from the passing of a charged particle through a scintillator. The light is then amplified in an image-preserving manner and recorded photographically. A chamber of useful size can be made from a single crystal or from a fiber bundle of scintillators. The use of this method of detection has been small because of the lack of suitable image intensifiers.

75.I "Luminescence Chamber." E. K. ZADOISKII, G. E. SMOLKIN, A. G. PLAKOV, AND M. M. BUTSLOV, Doklady Akad. Nauk. **100**, 241 (1955). The report of the first success with these devices.

76.I "Photography of Cosmic Rays in a Luminescent Chamber." M. L. PERL AND L. W. JONES, Phys. Rev. Letters **2**, 116 (1959). Describes results of photography and difficulties with image intensifier tubes.

IV. CONCLUSION

Since the development of particle detectors is an on-going enterprise, we enumerate here four types of literature resources which may be helpful to the user of this bibliography, as its contents will necessarily go out of date. The first of these are review anthologies which, based on past editorial policy, appear with some regularity and contain significant readings in the subject of particle detectors.

77.A Annual Reviews of Nuclear Science. E. Segrè, Ed. Published annually by Annual Reviews, Inc., Palo Alto, California.

78.A Handbuch der Physik. S. Flügge, Ed. Published irregularly by Springer–Verlag, Berlin, Germany.

79.A Progress in Elementary Particle and Cosmic Ray Physics. J. G. Wilson and S. A. Wouthuysen, Eds. Published irregularly by North-Holland Publ. Co., Amsterdam, Netherlands.

80.A Progress in Nuclear Techniques and Instrumentation. F. J. M. Farley, Ed. Published annually by North-Holland Publ. Co., Amsterdam, Netherlands.

81.A Progress in Nuclear Physics. O. R. Frisch, Ed. Published irregularly by Pergamon Press Inc., New York.

The second source of timely information is journals which devote themselves mainly to the description of the development as well as application of detectors.

82.A Nuclear Instruments and Methods. K. Siegbahn, Ed. Published fortnightly by North-Holland Publ. Co., Amsterdam, Netherlands.

83.A The Review of Scientific Instruments. J. B. H. Kuper, Ed. Published monthly by the American Institute of Physics, New York.

The unpublished literature of major laboratories where a great deal of the detector technology is developed is a substantial source of information. Specific technical reports may usually be obtained free from one of the authors or the Technical Information Office at the appropriate institution and all except 86.A for a fee from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia 20234.

84.A Argonne National Laboratory. University of Chicago, Argonne, Illinois 60439 (ANL).

85.A Brookhaven National Laboratory. Associated Universities, Inc., Upton, New York 11973 (BNL).

86.A CERN, European Organization for Nuclear Research. Geneva, Switzerland (CERN).

87.A Lawrence Radiation Laboratory. University of California, Berkeley, California 94720 (UCRL).

88.A National Accelerator Laboratory. Universities Research Association, Batavia, Illinois 60510 (NAL).

89.A Stanford Linear Accelerator Center. Stanford University, Stanford, California 94305 (SLAC).

The final source of current information on detectors and their application are symposia and proceedings from topical conferences, which are usually devoted to a particular device or technique. These appear irregularly, contain rather specialized accounts of detection techniques and are usually published in limited editions by various presses and governmental agencies.