Electron and Nuclear Counters

THEORY and USE

BY

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PREFACE

It is the purpose of this book to gather together and summarize the pertinent facts regarding the theory of the discharge mechanism and the practical operation of various types of counters. Although counters have been known for about forty years, they are even today surrounded by an atmosphere of mystery, and their construction and operation are claimed by many competent scientists to involve "magic." Various laboratories have developed special procedures for their manufacture and use, often without knowing why particular techniques appear to be successful.

This book first discusses the internal mechanism of the discharge in the counter. It then presents the constructional and operational features which are desirable, and the best means of securing them. Subjects discussed include the conventional Geiger counters as well as counters for special purposes and those selectively sensitive to particular types of particles, such as those which preferentially count neutrons in the presence of a strong background of gamma radiation.

The first chapter serves to introduce the subject, and to describe the progressive changes in counter behavior as the voltage is raised. The terminology to be used in describing counters is next defined. Then the operation of the instrument, first as an ionization chamber, then as a proportional counter, and finally as a Geiger counter, is developed and the theory and operation of each different type of counter is set forth. The practical aspects are next considered, and the construction of counters is taken up. The reasons for the various constructional features are given. The errors and corrections encountered in using these devices are discussed. Finally, the various electronic circuits, which are the essential auxiliaries to the successful operation of various kinds of counters, are presented.

The book is written on an intermediate level for users of counters, most of whom are persons with scientific training but who do not possess specialized knowledge in the field of Geiger counters. It presupposes an acquaintance with the main concepts of atomic physics, such as ionization, recombination, radiation and diffusion, as well as some familiarity with vacuum tube circuits. It is intended to be of use to graduate students and to the many industrial laboratories and medical research institutions which are finding counters to be useful tools of research.

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It is a pleasure to acknowledge the assistance received from many persons not only during the actual work of writing this volume, but more especially during the years while the author was acquiring the background information in this subject. It is probably true that most education is acquired by discussion of various aspects of the problems being studied with colleagues working in this and allied fields. The author was fortunate during the early 1930's in being able to confer about the background material with R. A. Millikan, H. V. Neher and John Strong, and subsequently with M. A. Tuve, L. R. Hafstad and L. F. Curtiss. Later he was equally fortunate in having many stimulating discussions with W. F. G. Swann, W. E. Ramsey, M. E. Rose, C. G. and D. D. Montgomery, G. L. Locher, W. E. Danforth and T. H. Johnson. He is especially indebted to his colleagues at New York University, R. D. Present, H. V. N. Hilberry and J. Simpson. The entire text has been read and checked for errors by Bernard K. Hamermesh. The drawings for the figures were made by Jane K. Hearn. Finally the author wishes to extend his especial thanks to Dr. J. A. Fleming of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington who gave important support to the study of counters at a time, during the early development period, when many persons doubted whether counters could ever be made into reliable and reproducible instruments of scientific measurement.

LIST OF SYMBOLS USED

A	The gas amplification
B	A constant
C	The electrostatic capacity, usually in microfarads
D	The standard deviation
E	The electric field in volts per cm
F	An area in sq cm
G	The efficiency
I	The current, usually in amperes
L	The Loschmidt number, 2.705×10^{19} molecules per cc at STP in a gas
N	Avogadro's number, 6.06×10^{23}
R	The resistance, usually in ohms
U	The volume, usually in cc
V	The potential in volts
Å	Ångstrom unit, 10^{-8} cm
a	The slope of the curve of ionization cross section as a function of energy
c	The velocity of light in vacuo
d	A distance
e	The charge on the electron. *Note:* Where the letter *e* is followed by an exponential, it is understood to be the base of natural logarithms 2.7183 . . .
h	Planck's constant
i	A flux or number of particles crossing a sq cm area per sec
k	The mobility
l	A length
m	The mass of the electron in grams
n	A number
p	The pressure of a gas, usually in atmospheres
q	The charge, usually in microcoulombs
r	A radius
s	The specific ionization, in ions per cm at STP
t	A time
v	A velocity
ev	Electron volt
Mev	Million electron volts
kev	Thousand electron volts
α	The first Townsend coefficient
β	The recombination coefficient
ϵ	An energy
λ	A wavelength
μ	The atomic weight
ν	A frequency
π	3.14159 . . .
ρ	A density
σ	A cross section, in sq cm

A letter or number with a bar over it designates an average value.

CONTENTS

CHAPTER 1

INTRODUCTION

A. History

Since the early experiments of Rutherford and Geiger, made nearly 40 years ago, it has been known that a useful device capable of counting individual atomic particles could be made by a combination of two electrodes in a gas. The device will detect the passage of charged particles through the volume between the electrodes and manifest this passage in the form of an electrical impulse. The apparatus will thus count the particles and is therefore called a *counter*. Counters have a wide variety of designs and uses. Almost anything can be made to count. One well known laboratory has an exhibit which consists of a fork and a spoon supported in air with a potential difference between them. This arrangement provides counting action and is a good, if somewhat extreme, illustration of the point that virtually any disposition of electrodes and gases can be used for the purpose. This situation has led to the publication of a great number of quasi-empirical papers, in which the several authors report that the particular combinations of gases and electrodes used will count. Unfortunately, these observations have generally been made in an unsystematic manner, with few controlled conditions, and are hence of little value, and sometimes quite misleading.

The problem of making counters into instruments of precision and of causing them to count quantitatively and accurately and to yield reproducible results is in no way insoluble, providing the basic factors are recognized. A great deal of work by a large number of investigators has been done on the problems pertaining to the construction and operation of these devices, and many theories regarding the functioning of counters have been evolved.

As early as 1908, Rutherford and Geiger [R1] arranged a cylinder and axial wire, applied a potential, and projected particles into the cylinder. They found that "the current through the gas due to the entrance of an alpha particle into the detecting vessel was magnified . . . sufficiently to give a marked deflection to the needle of an electrometer of moderate sensibility." They had devised the first counter, making use of the additional ionization produced by collision, as the electrons produced by the alpha particle traveled toward the central wire, to give an increase in the pulse size by a factor of "several thousand." Cylindrical symmetry in the distribution of the electric field was used from the first, and shortly thereafter Geiger's [G1] point counter, which employed spherical geometry, was developed. For some time, various types of filar electrometers [G2] were used to detect the pulses. These types were superseded as the rapid development of vacuum tubes during the two decades from 1920–1940 made electronic circuits possible which were faster, easier to adjust, readily portable and capable of amplifying the pulses as well as recording them. Counters with large sensitive areas were constructed in 1928 by Geiger and Mueller [G3] and have been generally called Geiger-Mueller counters.

The observation that at certain voltages the counter would detect alpha particles only, while at higher voltages it would detect both alphas and betas, was made in the early experiments. Later developments by Geiger and Klemperer [G4] in 1928 laid the foundation for the modern technique of "proportional counting" in which the difference in the ionization produced by an alpha and a beta particle is made the basis for distinguishing between them. Thus, proportional counters have been known about as long as any counters, although they were not so designated until much later.

The next important forward step resulted in the late 1920's from the recognition of the possibility of using counters in "coincidence" and the development of the techniques for this type of operation by Bothe and Kolhörster [B1], Rossi [R2], and Tuve [T1]. Widespread use of coincidence counters in cosmic ray measurements followed almost at once. Since counters had been shown to be versatile instruments, many investigators became interested in them and several contributed notably to the understanding of the manner in which these devices operated. The main motivation of these experimenters was not a desire to study counters, but the desire to prepare better instruments for their cosmic ray researches. The discovery of coincidence counting ushered in the modern period in the use and study of counters.

B. Present Uses

At the present time, counters are widely used in various branches of research and industry. In research, such devices usually serve to detect and record the number of particles emitted in various experiments involved in the study of nuclear radiation, disintegration and transmutation. These instruments are virtually indispensable in interpreting the data obtained by cyclotrons and Van de Graaff generators in that they enable the number of particles in a given beam, or the numbers produced in a given reaction, to be determined with accuracy. Counters are also used in ascertaining whether a bombardment has given rise to a radioactive product, and to determine the nature, the intensity, and period of the resulting activity. Similarly, they may be used to establish the identity and amount of naturally radioactive material or artificially activated substances. Neutron counters can be built to detect preferentially either fast or slow neutrons, and can therefore be used to measure the intensity of a neutron source, the number of neutrons in any given experimental arrangement, or the number diffusing out, from some apparatus into the surrounding room.

In cosmic radiation, counters constitute perhaps the most important single device for studying the nature and properties of the radiation and the ionizing secondaries which these rays produce. Further, by the use of electronic circuits described in Chapter 7, it is possible to impose on two counters the condition that only discharges nearly coincident in time shall be recorded. Such coincident discharges occur when a penetrating ionizing particle passes through both counters. Thus, we may determine the direction in which particles are traveling as well as the numbers that have traversed a given thickness of matter between the counters. This technique has been highly developed in recent years. It is now possible to analyze quite complex ionizing events, and to study the behavior of the rays and the many secondary processes which attend their passage through matter.

In medicine many uses for counters have also been found. Among these one may cite the detection of minute traces of radioactive substances in biological material, either radium and its decomposition products or artificially activated substances such as are commonly used in biological tracers. These studies may investigate the amount of substance introduced by accident or by design into a biological system, the distribution of the radioactive substance, and may follow the active material through various biological changes and through the parts of the system. Also, counters may detect and measure X-ray dosages and may be used to warn the operating personnel against possible overexposures, an effect of some importance when stray or scattered radiation is present in quantity. Similarly, fast or slow neutron dosages may be measured and counters may be used to ascertain effectiveness of protective procedures.

In industry, again, many uses have developed. These include detection of industrial tracers in which artificially activated substances may be followed through complex chemical and mechanical transformations, the location of lost tubes of radium, the detection of minute radioactive impurities, and the testing of samples of radioactive ores. In the study of petroleum geology, counters have found a use. A counter and a source of radiation may be lowered into an oil well boring, and the counter will measure the different amounts of radiation scattered back to it from the various strata of different materials through which the bore passes. This procedure can be made to reveal the location of hydrocarbon deposits, and the technique is in wide use today.

Neutron counters, being sensitive to neutrons, which in turn are strongly scattered by hydrogen-containing substances, have been used to detect the presence of hydrocarbon accumulations in the ground, or in pipes or other containers. An absolute altimeter has been proposed, in which the scattered neutrons would indicate water nearby, and the technique may be used for locating water.

In short, any industrial use of nuclear physics may be aided by using these instruments in the detecting procedures. It will be recalled that in metallurgy, diffusion phenomena, order-disorder studies, and tracer researches have made use of artificially activated substances. In each case, counters represent a useful detecting technique. Similarly in chemistry, the study of reaction rates, surface properties, molecular structure, low vapor pressures, equilibrium measurements, small solubilities, and catalysis have all been aided by the use of artificially radioactive elements. In each case a counter could be used to detect the activity, both in amount and in nature, and could follow the active substance through various changes and reactions. In geology, in addition to prospecting for radioactive deposits, identification of minerals, and assaying, counters have been employed in connection with artificially activated substances used in sedimentation studies.

It is the purpose of this book to describe the properties and behavior of counters and counting systems, and hence we next turn to a discussion of the electrical phenomena produced by counters.

C. Description of the Phenomena as a Function of Voltage

1. Low Voltage Region. Let us consider any system of the type ordinarily used for counting action, such as a cylindrical cathode and an axial wire anode. It is evident that the main function of the cylinder is to distribute the potential, and to form a volume in which the electric field is defined by the geometry of the electrodes. Suppose the wire of this system is connected to a sensitive device for measuring the voltage changes, (or pulses) which may appear on it, such as an oscilloscope with high amplification; let us consider the pulse sizes and distributions as the voltage across the counter is raised. Such a counter will then form a part of the fundamental circuit shown in Fig. 1–1, in which the cross section of a counter is depicted, a potential is applied across it, and a resistance R inserted in order that a pulse may be passed to the detecting unit. The condenser C is understood to include all the distributed capacity in the circuit. The recovery of the wire after a pulse has occurred is controlled by the familiar exponential RC time constant and cannot be made shorter than this value but can, of course, exceed this figure if the discharge conditions are suitably varied. We shall assume that curves of the number of counts at various voltages are obtained, while the flux of radiation passing through the counter is kept constant. We shall consider the wire to be positive with respect to the cylinder and shall therefore discuss the collection of negative ions and elec-

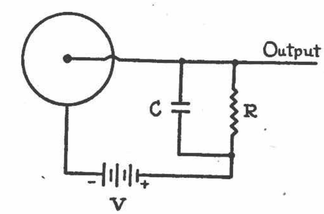

Fig. 1–1. Fundamental counter circuit.

trons on the central wire. The operation of the counter in various voltage regions will be described. We shall show how this device functions at low voltages as an ionization chamber. As the voltage is progressively raised, the device becomes in turn a proportional counter and a Geiger counter. We thus have several voltage regions: the low voltage region, the proportional region, and the Geiger region, in which quite different types of phenomena occur, and in which the same counter may be used for quite diverse purposes. We shall consider these in turn.

The word "ionization" is used in physics in two distinct senses. In the narrow sense it means the process of removal of an electron from a neutral atom. We shall use it in its broader sense, to mean any act or process by which a molecule or atom which was neutral acquires a charge, or by which electrons are freed in a gas. We shall also use the word to describe the results of the process, in the sense that we may say that "ionization has been produced in the gas." We are less concerned with the nature of the event causing the ionization, and more interested in the collection of the charges produced and in all the processes which accompany this collection. The reader will recognize that we must therefore discuss electrical discharges in a gas. Since this book cannot also be a treatise on gas discharges, we shall assume some acquaintance with the subject and refer the reader to standard texts for further details. We shall now examine the results which follow when ionization is produced in a counter.

It will be recalled that when ionization is produced, in general an ion-pair, positive and negative, is formed from what was initially a neutral atom. We must consider what happens to both of these fractions as they are drawn, respectively, to the negative and positive electrodes. For the sake of simplicity we shall discuss these two parts separately, but it must always be kept in mind that both are present and that their interactions must be considered.

At zero voltage across the counter, there will be no fluctuations in the potential of the central wire, save those caused by the random arrival of individual ions on the wire. If a small voltage is applied, a field is established in the space between the cathode and anode, and any positive ions formed in this volume tend to drift toward the cylinder, and the negatives toward the wire. As the voltage is first applied on the cylinder, the arrangement becomes in effect an ionization chamber in which any electrons produced in the volume of the counter are swept by the field to the central wire where they are collected. The size of the voltage pulse appearing on the central wire is determined by the number of charges arriving and by the distributed capacity of the central wire and anything attached electrically to it, such as the grid of the tube in the first stage of the amplifier. The wire potential will also be subject to a transient influence if a positive space charge exists. A change in potential, dV, will be produced by the arrival of a charge, dq, on an electrode of capacity C. In terms of the arrival of particles of unit electronic charge equal to 1.60×10^{-19} coulombs, the rise in potential of the central wire will be given by

$$dV = dq/C = 1.60 \times 10^{-7} n/C \qquad (1\text{–}1)$$

where n is the number of electrons arriving, dV is the rise in potential in volts, and C is in micromicrofarads. Eq. (1–1) assumes no effect of positive space charge and hence is correct *after* the positives have been collected. The changes in potential of the wire, while the positives are moving out to the cylinder, will be discussed later.

The time rate of change of the voltage is determined by the rapidity with which the ions are collected on the central wire, providing this is small compared to the time constant RC. To know this, we must know the mobility of the charged particles collected, which for negative ions is of the order of 1.2 to 1.4 cm per sec per volt per cm referred to air at standard tempera-