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Title of Study: SOME PROBLEMS, PRINCIPLES, AND PROJECTS ON THE DETECTION AND IDENTIFICATION OF RADIOACTIVE PARTICLES AND SHORT WAVELENGTH RADIANT ENERGY

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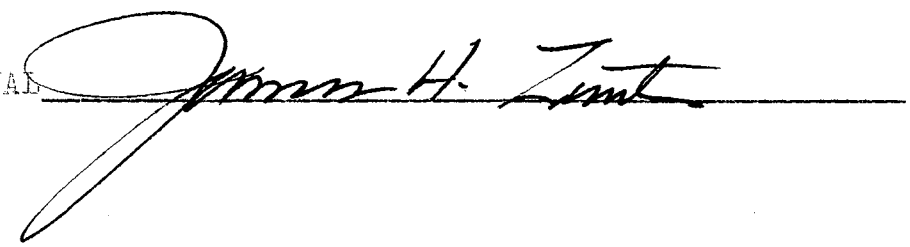
Scope and Method of Study: The library was searched for information about the problems and principles involved in the detection and identification of short wavelength radiant energy and of radioactive particles. Projects for high school use were chosen for safety and reasonable cost.

Findings and Conclusions: The problems of detection and identification of short wavelength radiant energy and of radioactive particles arise because the photons and particles are invisible. Some effect caused by interaction of a photon or particle with matter must be used to detect the photon or particle. Identification is done by comparison of the effect with effects caused by known photons and particles.

The effects used are ionization, excitation followed by radiation of visible photons and temperature changes. Some of the instruments using these effects are photographic plates, thermopiles, bolometers, ionization chambers, proportional counters, Geiger counters, cloud chambers, and electroscopes.

The projects recommended for high school are those which are safe because they involve low activities and those which are reasonable in cost. These include use of photographic methods, construction and use of cloud chambers, construction and use of Geiger counters, and construction and use of electroscopes.

ADVISER'S APPROVAL 

SOME PROBLEMS, PRINCIPLES, AND PROJECTS ON THE DETECTION AND IDENTIFICATION OF RADIOACTIVE PARTICLES AND SHORT WAVELENGTH RADIANT ENERGY

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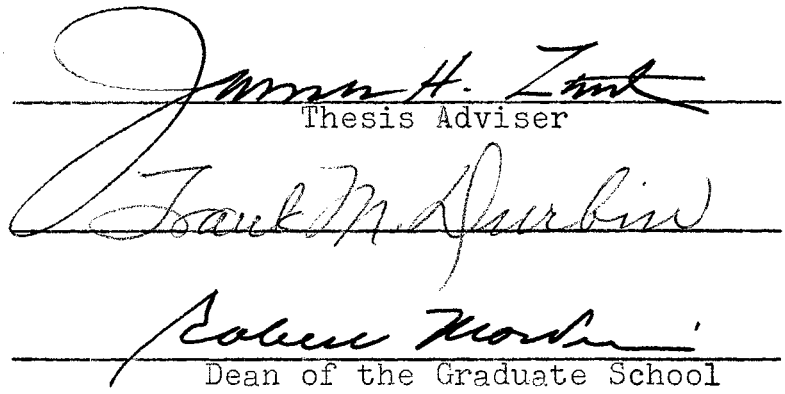

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CHAPTER I

INTRODUCTION

The study of radioactivity and radiant energy has been assuming ever increasing importance in the affairs of man and seems destined to continue this trend. Man has always been aware of radiation in the forms of heat and light, but he knew little of the nature of these before Newton about 1665 showed that radiation from the sun could be separated into a spectrum. He knew nothing of other radiations before Herschel in 1800 discovered considerable energy beyond the red end of the visible spectrum. In 1801 Ritter discovered the ultraviolet region by its effect on silver chloride. In 1888 Herz proved the existence of long wavelength radiation now called radio waves. In 1895 Rontgen discovered x-rays. In 1900 Villard discovered gamma rays. Since then the gaps in the total electromagnetic spectrum have been gradually filled by improved techniques and improved instruments. In addition to the electromagnetic spectrum several radioactive particles which transmit energy have been discovered and identified in the first part of this century.

The modern discoveries, inventions, and problems dealing with radioactivity and solar energy are played up in the popular magazines and newspapers. One of the results is an intense interest on the part of high school students who ask

questions about what they have read. Some of them desire experiments and projects that they can do for their own benefit or for science fairs.

The logical sources of information are the teachers and the high school books. The average high school teacher of physics has two or three physics courses in his college background at the most, and his knowledge of radiations and emitted particles is limited to a brief introduction to radio, heat, and light. The average high school physics text, as shown by an inspection of five high school texts found in the Oklahoma State University library, contains several chapters on heat, light, and radio, but it contains only a few pages on radioactivity and barely mentions radiations of wavelength shorter than the visible. A survey of the corresponding workbooks and laboratory manuals showed that the average one contains several experiments on light, heat, and radio, but only one has an experiment on x-rays, and only one has an experiment on radioactivity.

It seems important <u>not</u> to discourage these interested students. Therefore, this report reviews the problems of detection and identification, discusses the principles involved in some of the principal instruments, and points out some projects suitable for high school students.

CHAPTER II

THE PROBLEMS OF DETECTION AND IDENTIFICATION

The problem of detection arises because all the rays from radioactive materials and all the electromagnetic waves are invisible except a narrow band. Therefore, detection depends upon some effect of radiation or emitted particles that can register on human senses.

The effects a photon or particle can produce depend upon the energy it possesses. The energy of a photon can be calculated by using Planck's quantum theory. The equation is $E=h\nu$ where E is the energy in ergs, when h is Planck's constant, 6.62×10^{-27} erg-sec., and ν is the frequency in cycles per second. Table one gives the energy calculated for the limits of the various subdivisions of the electromagnetic spectrum given by Durbin.[1]

The energy of a particle is the kinetic energy it possesses. This is represented by the formula $K.E.=\frac{1}{2}mv^2$ where K.E. is in ergs when m is in grams and v is in centimeters per second. The mass and the velocity of a particle thus determine the amount of energy available with which to cause effects. This energy may vary from zero to several million

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[1]Frank M. Durbin, Introduction to Physics (Englewood Cliffs, N. J., 1955) p. 481.

TABLE I

LIMITS OF THE SUBDIVISIONS OF THE
TOTAL ELECTROMAGNETIC SPECTRUM

Subdivision	Wave Length Limits in cm.	Frequency Limits in vibrations/sec.	Energy limits in ergs	Energy limits in eV
Electric	$1x10^{12}$ to $1x10^{6}$	$3x10^{-2}$ to $3x10^{4}$	$1.98x10^{-28}$ to $1.98x10^{-22}$	$1.24x10^{-16}$ to $1.24x10^{-10}$
Radio, Radar Television	$3x10^{6}$ to $7.5x10^{-2}$	$1x10^{4}$ to $4x10^{11}$	$6.62x10^{-23}$ to $2.65x10^{-16}$	$4.14x10^{-11}$ to $1.65x10^{-3}$
Infrared	$4x10^{-1}$ to $8x10^{-5}$	$7.5x10^{10}$ to $3.8x10^{14}$	$5x10^{-16}$ to $2.5x10^{-12}$	$3.1x10^{-4}$ to 1.55
Visible	$8x10^{-5}$ to $4x10^{-5}$	$3.8x10^{14}$ to $7.5x10^{14}$	$2.5x10^{-12}$ to $5.0x10^{-12}$	1.55 to 3.1
Ultraviolet	$4x10^{-5}$ to $8x10^{-7}$	$7.5x10^{14}$ to $3.8x10^{16}$	$5x10^{-12}$ to $2.5x10^{-10}$	3.1 to $1.55x10^{2}$
X-rays	$1.5x10^{-6}$ to $3x10^{-10}$	$2x10^{16}$ to $1x10^{20}$	$1.3x10^{-12}$ to $6.6x10^{-7}$	$8.1x10^{-1}$ to $4.14x10^{5}$
Gamma rays	$1.5x10^{-8}$ to $4x10^{-11}$	$2x10^{18}$ to $7.5x10^{20}$	$1.3x10^{-8}$ to $5x10^{-6}$	$8.1x10^{3}$ to $3.1x10^{6}$
Secondary Cosmic rays	$3.8x10^{-11}$ to $3x10^{-15}$	$8x10^{20}$ to $1x10^{25}$	$5.3x10^{-6}$ to $6.6x10^{-2}$	$3.3x10^{6}$ to $4.1x10^{10}$

electron volts depending upon the source of the particle.

Photons, having no mass or charge, can easily pass between the atoms of a substance until they are finally absorbed. This absorption can result in several effects which depend upon the energy of the photon and other factors not yet clearly understood. First, it may move an electron from one energy level to a greater energy level in the same atom. Second, it may give the entire atom greater kinetic energy thus raising the temperature. This occurs when the photon excites the atom which then has a collision of the second kind with another atom. Molecules may have their kinetic energy increased by a process which is the reverse of bond spectra emission[2] Third, it may remove an electron from the atom thus producing ions. Fourth, part of its energy may accelerate a free electron and the remainder become a photon of lesser energy. Fifth, it may become a position-electron pair in the intense electric field of a heavy nucleus.

According to Semat[3] the electron in a hydrogen atom exists in definite energy levels. This atom is the simplest, but even so it exhibits an infinite number of energy levels. The difference in energy of these levels from the ground level

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[2]Floyd K. Richtmyer, Introduction to Modern Physics (First ed., New York, 1928), p. 392.

[3]Henry Semat, Introduction to Atomic and Nuclear Physics (Third ed., New York, 1954), p. 225.

varies from 10.2 eV to 13.6 eV, the ionization potential. To cause an electron to move out to another energy level exactly the amount of energy represented by the difference in total energy, potential and kinetic, is required.

To cause ionization a photon must have energy equal to or greater than the ionization potential energy. Table II[4] gives ionizing potentials for some metals used as photo-cathodes. Table III[5] gives some ionizing potentials for gases. The energy needed to produce a position-electron pair is a minimum of 1.02 million electron volts.[6] The possible effects of an electromagnetic wave are easily found by comparing its energy with that needed for the various effects. For example, from Table III, O_2 needs 12.5 eV for ionization. From Table I all photons above ultraviolet and including the longer wavelength ultraviolet cannot ionize O_2.

Of course the effects of photon absorption must be something that can register on man's senses or produce a secondary effect which can register. The excitation of an atom by moving an electron to a greater energy level is not visible, but when the electron moves back toward the ground level in one or more steps, electromagnetic waves are given off. If these are within the visible region, they may be seen with the eye or with a microscope, or, visible or not, they may

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[4]Arthur Llewelyn Hughes, Ionization of Gases and Vapors by Ultraviolet Light (St. Louis, 1929), p. 6.

[5]Ibid., p. 31.

[6]Semat, p. 435.

TABLE II

IONIZING POTENTIALS OF THE ALKALI METALS

Element	Ionizing Potentials in eV
Li	5.368
Na	5.116
K	4.321
Rb	4.159
Cs	3.877

TABLE III

IONIZING POTENTIALS OF VARIOUS GASES

Gas	Ionizing Potentials in eV
O_2	12.5
N_2	16.3
H_2	15.8
CO	14.1
CO_2	14.3
NO	9.5
CH_4	14.4
C_2H_6	12.8
C_2H_4	12.2
C_2H_2	12.3
Cl_2	13.2
Br_2	12.8
I_2	10.0
HCl	13.8
HBr	13.2
HI	12.8
NH_3	11.1
H_2S	10.4
H_2O	13.2

produce, as a secondary effect, the photoelectric effect which is detectable by various instruments. Heat is not visible and so must produce a secondary effect. Ions are not visible and must also produce secondary effects to be detectable.

Particles are divisible into two classes, charged and uncharged. Charged particles produce, as their main effect, ionization in the atoms along their paths by the interaction of electric fields. On the average, a charged particle loses about 32 eV of energy for each pair of ions formed.[7] If the number of ion pairs can be determined, the energy can be calculated.

Uncharged particles do not produce ionization by interaction of fields since they have no field. Their effects depend upon collisions. They can cause excitation within an atom or ionization by collision with external electrons. Their main effect however is to collide with a nucleus transferring most of their energy to it if it is about the same mass. This positively charged nucleus then produces ionization effects.

The only effect directly observable is fluorescence when excitation energy is given off as visible rays. The other effects require special treatment or equipment to be observable.

The problem of identification arises because the same effect can be produced by more than one radiation. Electromagnetic waves can be identified by separating them by prisms

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7Durbin, p. 648.

or diffraction gratings and comparing them with the lines of a known radiation. X-rays and gamma rays can be diffracted by crystal gratings and their wavelengths calculated from the Bragg equation, $n\lambda=2d \sin \theta$.

The identification of particles depends upon comparing the effects they cause with the effects caused by a known particle. For a charged particle the magnetic spectrometer can be used.

CHAPTER III

SOME INSTRUMENTS FOR DETECTION AND IDENTIFICATION OF RADIATION AND EMITTED PARTICLES

To be discussed here are photographic, scintillation, ionization, and total absorption devices.

Photographic Methods

The principle upon which the photographic plate depends is that the energy of a photon or particle excites the molecules, usually Ag Br or Ag I, embedded in a gelatine emulsion on the film and causes a molecular change. This changed material contrasts with its surroundings, and, after development to fix it permanently, the amount of change can be measured by various means.

Photographic materials are sensitive receivers of the selective type. They can be used to measure radiant energy in absolute terms only after having been calibrated by some form of nonselective receiver, such as a thermopile, a bolometer, or a vane radiometer.

Some advantages are:

1. It may be used for recording simultaneously the relative intensities of a large number of different samples of radiant energy.

2. It gives a permanent record of these intensities.

3. It is a receiver of the integrating type, and hence in the case of very low intensities the response can be increased up to easily measurable magnitudes by making the exposure times long.

4. Average values of variable intensities for definite time intervals may be obtained.

5. Due to its integrating characteristic, its effective sensitivity is greater for very low radiation intensities than that of the nonselective radiation-sensitive elements.

Some disadvantages are:

1. Photographic materials differ considerably; therefore, the characteristics of the one in use must be accurately known.

2. The response depends on many factors which must be controlled in order to get accurate results. Some of these factors are:

a. length of time of exposure.

b. the rate at which the radiant energy falls upon the film.

c. extent of development.

d. intermittent or continuous exposure. It does not integrate correctly on intermittent exposure.

e. growth or decay of the latent image after exposure and before development.

f. variations of sensitivity from point to point on the film.

To determine the amount of energy received one must control or eliminate all the variables and compare the result

to the result caused by a known amount of radiation. The easiest way to do this is to expose small sections of the film which are close to each other simultaneously to the unknown radiation and to the calibrating radiation and for the same length of time. Comparison of the densities will give the amount of radiation if the radiations have the same spectral composition. If the spectral compositions are different, the calibrating radiation will have to be varied in known steps, each step recorded on a small section of the plate. Then comparison of the unknown with each small section will identify the amount of radiation fairly accurately and also the wavelength.

If the unknown radiation is a mixture of various wavelengths, the amount of energy can be determined as above, but identification of the different wavelengths is impossible until they are separated. For ultraviolet this can be accomplished by sending it through a quartz or fluor-spar prism or diffraction grating spectrometer. Comparison with lines caused by known wavelengths will identify it. X-rays and gamma rays can be separated into wavelengths by crystal diffraction before photographing and their wavelengths calculated by the Bragg equation.

Obviously, simple detection with a photographic plate is easy. Expose a part of the film to the suspected source. Develop the whole film. Compare the exposed part to that part next to it. If there is any difference, it must be from the suspected radiation.

Sometimes there is a problem of excluding unwanted radiations while allowing the desired ones to affect the film. An example is testing for gamma rays in daylight around an installation. The visible and ultraviolet must be excluded. This is easily done by wrapping the film in black paper, which filters out all radiations of low energy.

Particles can be detected and identified by photographic plates also. Allow the particles to strike the plate. Then develop it and compare the length and size of the tracks with those made by known particles on similar film. This comparison must be done under a microscope.[1]

Non-Selective Instruments

Among the non-selective instruments are the bolometer, thermocouple, and thermopile.

The bolometer consists essentially of two nearly identical, very thin strips of metal, usually platinum, which form two arms of a Wheatstone bridge. These strips are cut initially to correspond to a desired width of slit or purity of spectrum. They are blackened on one side only. In use one strip only is exposed to the radiation to be measured while the other is protected from it. With the bolometer bridge initially balanced, absorption of energy by one of the strips results in raising its temperature, increasing its

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[1]L. A. Jones, "Measurements of Radiant Energy with Photographic Materials," Measurement of Radiant Energy, ed. William E. Forsythe (New York, 1937), pp. 246-267.

electrical resistance, and destroying the bridge balance. A deflection of the galvonometer results.

Placing the bolometer strips inside a glass enclosure which is evacuated to less than .001 mm. pressure increases its sensitiveness tenfold. A diagram of the Smithsonian vacuum bolometer is given by Aldrich.[2] Calibration is made by exposing the bolometer to a source of known radiant intensity.

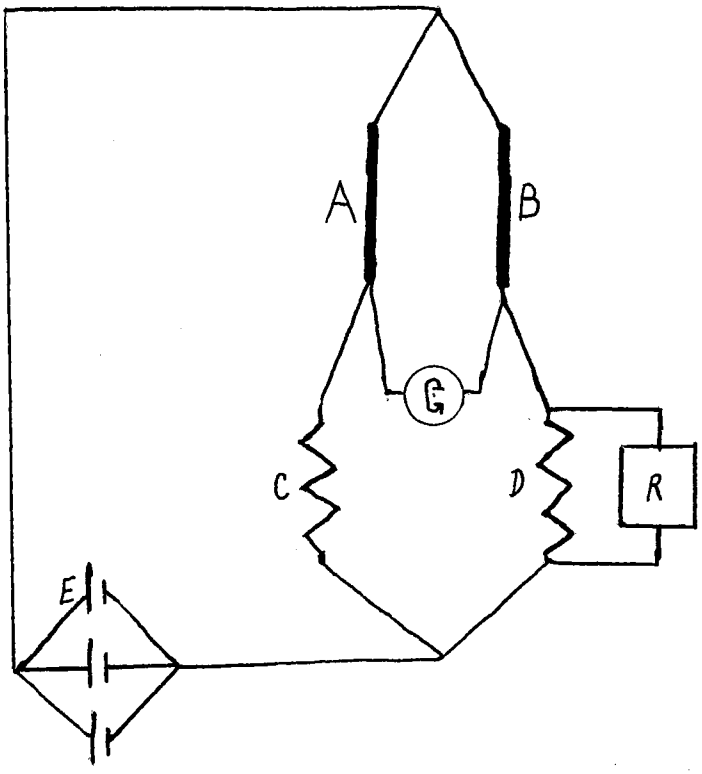

Figure 1. Bolometer Circuit

R - variable resistor
C and D - Wire resistance coils
A and B - Blackened metal strips
G - galvanometer
E - dry cells

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[2]L. B. Aldrich, "The Bolometer", Measurement of Radiant Energy, ed. W. E. Forsythe (New York, 1937), p. 208.

Thermocouples and Thermopiles

A thermocouple is a pair of dissimilar electrical conductors joined so that an electromotive force is produced when the junctions are at different temperatures.[3] Many combinations of metals have been used; e.g., copper-constantan, iron-constantan, chromel-alumel,[4] bismuth-silver,[5] etc.

A thermocouple is calibrated by adjusting the temperature to a few fixed points such as the temperature of boiling water, freezing water, freezing point of mercury, freezing point of tin, and measuring the electromotive force produced.[6] This yields a working standard which is accurate to a few tenths of a degree.

In use the reference junction is kept at a constant temperature by placing it in a small vial and immersing it in water and melting ice at 0 degrees C. The electromotive force is usually measured with a galvanometer, millivoltmeter or potentiometer.[7] The "hot" junction is exposed to the radiation so that absorption may take place. It may be coated black to increase absorption almost to one hundred per cent. This junction may be embedded in a plate to increase the area,

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[3]Robert L. Weber, Temperature Measurement and Control (Philadelphia, 1941), p. 45.

[4]Ibid., pp. 68-70.

[5]Forsythe, pp. 192-3.

[6]Weber, pp. 72 and 85.

[7]Ibid., p. 84.

or a collection mirror may be used to increase the radiant energy falling on the thermocouple.

To make a thermocouple more sensitive several of them may be connected in series and half of the junctions exposed and half kept at a constant temperature. This instrument, a thermopile, can detect very small changes in temperature. A sensitive galvonometer is usually used to measure the electromotive force.[8]

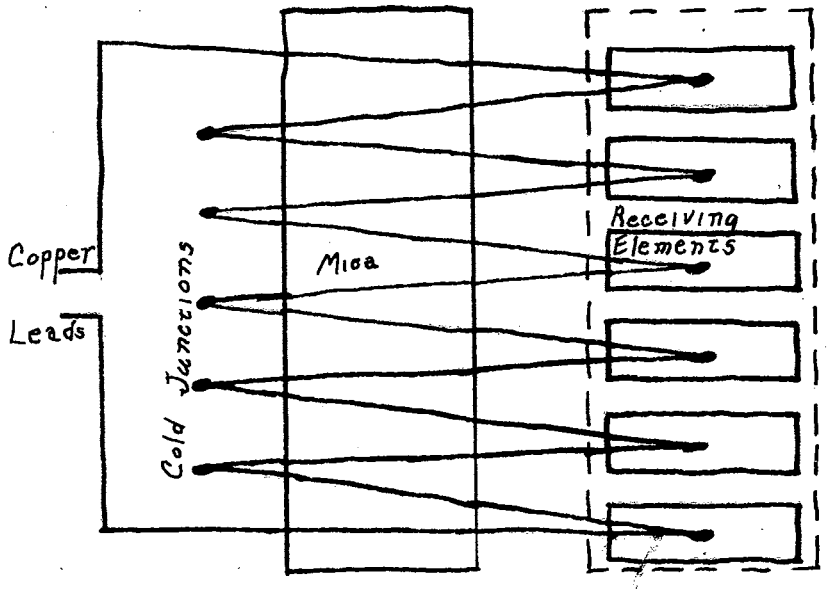

Figure 2. Thermopile

This instrument can be used selectively by using it with filters or spectroscopes.

Ionization Devices

Whenever the ionization effect occurs it can be used to help detect or identify the particle or electromagnetic wave

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[8]Ibid., p. 67.

that caused the effect. Several devices are in use for showing that ionization has occurred and for measuring its amount. Some of these are the Wilson Cloud Chamber, the electroscope, the ionization chamber, the proportional counter, and the Geiger-Muller Counter.

The Wilson Cloud Chamber

The cloud chamber works on the principle that water vapor condenses on ions in a supersaturated space. If, by any means, the space in a container is supersaturated, the passage of an ionizing particle will be followed by the formation of a cloud along the path.

There are two methods by which the space in a container becomes supersaturated. (1) The air is allowed to become saturated by standing in contact with water. Then a sudden expansion will lower the temperature and cause the space to be supersaturated. (2) The second method is by maintaining the top and bottom of the chamber at different temperatures. The top of the chamber is maintained at a temperature that will vaporize the liquid. The bottom is maintained at a colder temperature by a refrigeration device or dry ice.

One of the difficulties is the condensation of the vapor on other media besides ions. In particular dust acts as a good condensing medium. This can be eliminated by expanding and contracting the chamber a few times so that water droplets form on the dust and cause it to fall to the bottom. Dust can be eliminated from the constant volume chamber by allowing it

to stand at the working temperatures for an hour or two before use.

Uncharged small nuclei, probably aggregates of a few molecules, and re-evaporation nuclei also serve as media for cloud formation. These can almost be avoided by operating the chamber at a lower supersaturation than that needed to cause cloud formation on uncharged small nuclei. Condensation on re-evaporation nuclei cannot be avoided if they are present. A series of cleaning expansions are used to sweep them out after each expansion to the ion limit.

An electrostatic field is often used for clearing the chamber of ions and preparing it for the next event. Also, the direction of curvature of a path in this field indicates the sign of the particle's charge. Where the track begins indicates whether it is a primary or secondary effect.

For a permanent record a photograph may be made of a track. For very accurate work the photographs need to show single drops. It is hard to determine exact origin of a particle in a cluster or to determine recoil spurs of a very few drops in a cluster.[9]

The Electroscope

The electroscope operates on the principle that like charges repel and unlike charges attract. The electroscope

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[9]J. G. Wilson, The Principles of Cloud Chamber Technique (Cambridge, England, 1951), pp. 1-57.

consists of two leaves or fibers with a common base or connection. When the leaves are charged positively or negatively they fly apart because of the repulsion of like charges. They remain apart until the charges are neutralized. Any particle or electromagnetic wave with energy enough to ionize the gas in the electroscope flask or container contribute to the discharge of the electroscope. The rate of discharge indicates the approximate intensity of radiation but does not identify the radiation.

Counter Tubes

Counter tubes have been made in a large variety of sizes and shapes for various purposes. As shown in figure 3 most counter tubes consist of a glass tube with a wire through the center and a metal cylinder around the inner side of the glass. A potential difference is applied between the wire and the cylinder, the latter being negative. This potential difference causes negatively charged particles to move to the wire and positively charged particles to move to the cylinder. The potential difference determines whether the tube serves as an ionization chamber, proportional counter, or Geiger-Muller counter.

For a given tube the gas-amplification will vary with the voltage applied to the tube. Experiment yielded the curve of figure 4 for a given tube. The curves for other tubes with different geometries and different gases are similar in shape, but the points on the curves vary in position.

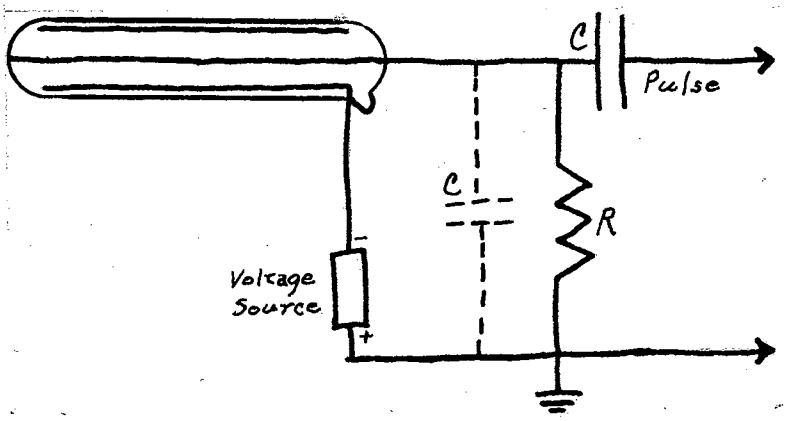

Figure 3. Basic Counter Circuit[10]

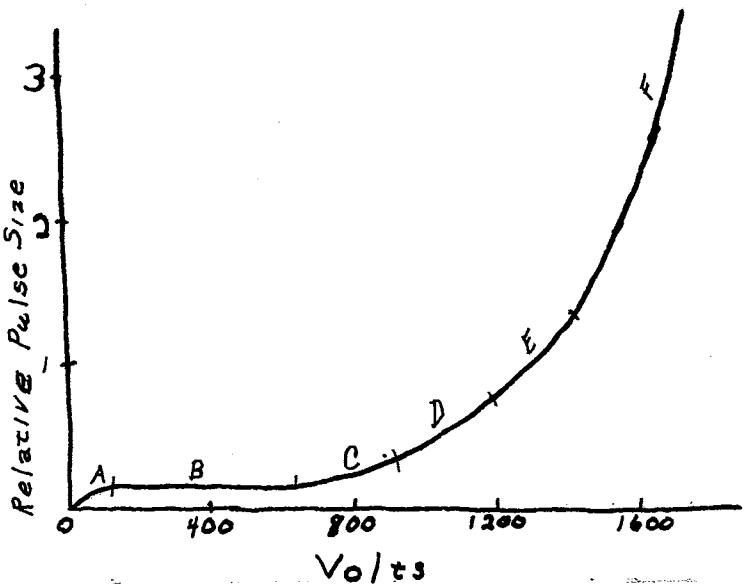

Figure 4. Pulse size as a function of the applied voltage. The vertical scale has been greatly compressed, the size at F being about 10^8 times the size at B.[11]

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[10]S. C. Curran and J. D. Craggs, Counting Tubes (New York, 1949), p. 2.

[11]Ralph E. Lapp and Howard L. Andrews, Nuclear Radiation Physics (2nd ed., New York, 1954), p. 226.

In figure 4 at zero voltage the pulse size is zero. This is because there is no electric field to cause the ions to move to the collecting electrodes. In region A because of recombination and diffusion of the ions less electrons are collected than were formed by the ionizing event. In region B very nearly the same number are collected as were formed. In region C more electrons are collected than were formed by the initial ionizing event, and the number is proportional to the initial amount of ionization. In region D tone proportionality is not obtained. In region E the pulse size is entirely independent of the amount of initial ionization in the tube. Above E a continuous glow discharge is obtained.[12]

Ionization Chambers

A tube operated in region B of figure 4 is called an ionization chamber. The potential difference is not enough to accelerate the electrons formed by the ionizing event to the point where they can cause further ionization on their way to the anode. However, the potential difference should be enough to prevent recombination of the ions. This seems to be the most direct method of measuring the energy of ionizing particles.

A look at region B of figure 4 shows that the voltage can vary considerably without causing the size of the pulse

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[12]Curran and Craggs, pp. 24-25.

to change. If the ionizing events are occurring continuously, these pulses amount to a current flowing from the anode through an external circuit to the cathode. The collected charge can be measured with an electroscope or electrometer. In some cases the pulse can be amplified and used to operate mechanical counters, etc.

Most of the problems of counting the pulses are concerned with the electronic circuits and components for amplification. There might be a noise level at the first grid of about 10^{-5} root-mean-square volts. The output of the ionization chamber must exceed the noise level if it is to be detected and measured. It is just possible to detect and count alpha particles which have produced a track of only one millimeter in the chamber. Sometimes high speed electrons can pass through the chamber without producing enough ions to exceed the noise level. Some chambers are operated above atmospheric pressure to increase the charge produced. Sometimes large ionization chambers are used with integrating circuits rather than with amplifiers. Approximately 2000 ion pairs is a practical lower limit.[13] By using a large time constant for the circuit of the collecting electrode, a time constant much larger than the time of collection of the ions, the change of potential of the electrode measures the ionization produced.[14]

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[13]Ibid, p. 39.

[14]Ibid, pp. 25-29.

Proportional Counters

Tubes operated in region C of figure 4 are called proportional counters because the number of electrons reaching the anode is greater than and directly proportional to the number of ion pairs produced by the ionizing event. The electric field is sufficiently intense to give the electrons energies adequate to create additional ion pairs as they pass through the gas toward the anode. If the field is this intense throughout the tube, the length of the path of the electron moving toward the anode determines the size of the charge collected. To prevent the point of formation of an ion pair from determining the size of the avalanche the geometry of the tube is arranged so that the electric field in most of the volume is too weak to cause gas amplification but near the anode the field is strong enough to cause gas amplification. Usually this is a cylinder as the cathode with a wire through the center as the anode. Errors can be caused by photoelectrons produced in the gas or at the cathode or by fluctuating voltage. If the tube has gas amplification of about 2000, it can detect one ion pair formed in the sensitive volume. Organic vapors present in the noble gas or other simple gas absorb photoelectrons and disintegrate. This stabilizes the tube until all the organic vapor is disintegrated. The proportional tube can be made to resolve pulses separated by about one microsecond. The pulses can be calibrated by using particles of known energies such as

alpha particles from polonium. The external electronic circuit can be adjusted to respond only to pulses larger than a desired size. Thus, it can be used to count alpha particles in the presence of beta and ganuma rays.[15]

Geiger-Muller Counters

A tube operated in region E of figure 4 is called a Geiger-Muller counter. Its gas-amplification factor may be as high as 10^8. Ultraviolet photons from excited gas molecules returning to their ground states eject photoelectrons from the cathode. Positive ion bombardment of the cathode may eject electrons. Positive ion collisions with the gas molecules may cause emission of electrons from the gas. Any single electron can start a secondary avalanche. The original avalanche spreads along the entire length of the central wire. Therefore the size of the output pulse is independent of the number of primary ions, and the tube cannot distinguish between the various types of particles or photons.

If the counter tube be connected to electronic equipment for recording the number of pulses and the tube be exposed to a constant radiation intensity, the number of pulses counted per minute when plotted against the tube voltage will give a characteristic curve similar to figure 5.

Because the electronic counting equipment associated with the tube needs a certain minimum amount of current to operate,

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[15]Ibid., pp. 29-52.

any pulses less than this minimum will not be counted. Generally the pulses in the ionization-chamber region and in the lower proportional region are below this minimum amount. As the voltage is increased, a voltage will be reached at which the first count is recorded. This is point A in figure 5. It is called the threshold. These first counts are the most ionizing particles. As the voltage is increased gas amplification increases so that less energetic particles are counted. After point C is reached further increases in voltage, although they increase gas amplification, do not increase the number of counts per minute. Almost every particle entering the tube is counted. Point C is called the Geiger threshold, and C D is called the Geiger plateau. It can be seen from figure 5 that variations of voltage between C and D have little effect on the number of counts per minute. This is the best region to operate the counter in for stable operation. Above D there is so much gas amplification that more than one pulse is produced and unstable operation results.

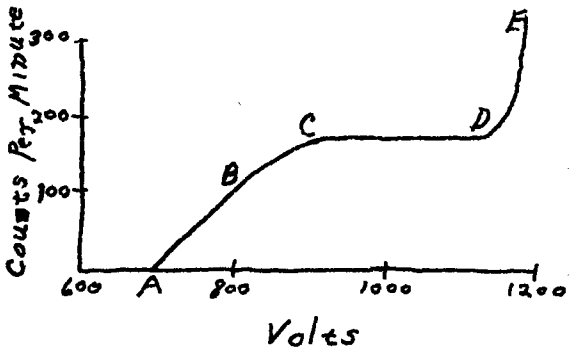

Figure 5. A typical G-M Counter characteristic curve.[16]

[16]Lapp and Andrews, p. 229.

A Geiger-Muller counter operating on its plateau will have avalanche following avalanche until conditions change enough to stop it. When gas amplification takes place near the anode equal numbers of positive and negative ions are produced. The positive ions have much larger mass than the negative ions, electrons, and therefore accelerate much more slowly in the electric field than the electrons. The result is a sheath of positive ions around the anode after the electrons reach the anode. This space charge reduces the electric field near the anode and stops the gas amplification. Another avalanche will start when the positive ion approaches close to the cathode. The positive ion pulls an electron from the cathode to become neutral. The electron moves to the ground state and radiates photons. Some of these will be ultraviolet and will liberate photoelectrons from the cathode. These photoelectrons start another avalanche.

There are two ways of preventing this second discharge, the use of large resistances in series with the anode and the use of a self-quenching tube. If the resistance, R, in figure 3 is 10^9 ohms or larger, the electrons will not leak off the anode very rapidly. This accumulation of electrons on the anode lowers the potential difference below the gas amplification point and prevents an avalanche from photoelectrons from the cathode. Then the electrons must leak through the resistance until the original voltage is restored. This takes about 10^{-2} second. If external quenching circuits are used, the dead time is determined by the time of movement of the

positive ion sheath to the cathode. This is about 10^{-4} second.

The use of a self-quenching tube stops the second discharge in a different manner. This tube contains organic vapors or halogen which absorb the photoelectrons from the cathode and the photons. The organic vapors dissociate instead of reradiating the energy. The life of the tube is limited to the number of ionizing events necessary to disintegrate all of the organic vapor. Use of the halogens as quenching agents prolongs the life of the tube because the dissociated atoms recombine.[17]

The Scintillation Counter

In its simplest form the scintillation counter consists of a screen of a suitable material, for example zinc sulphide, which gives off light flashes when struck by ionizing particles or photons. The counting is done by the human eye. This works well for short periods of time and slow rates.

The modern scintillation counter works on the same principle except that the human eye has been replaced by a photomultiplier capable of delivering large pulses of current of short duration, one per scintillation, and these can be registered directly by almost any electronic device currently in use for such purposes.

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[17]Ibid., pp. 228-234.

The advantages are: (1) it is free from microphony and fragility of any kind, (2) it can count at rates higher than those possible with any other device, (3) it can be used proportionally and much knowledge of the nature and energy of the radiations can be deduced from the pulse amplitudes.

In its elementary form the scintillation counter takes the shape indicated in figure 6. A source S emits particles or photons which fall on the luminescent crystal. This may be a thin layer of microcrystals of activated zinc sulphide, or a single large crystal of an inorganic substance such as sodium iodide (activated with thallium), or an organic crystal such as anthracene. It may be a vessel containing a liquid such as a solution of terphenyl in xylene. A photomultiplier tube with a photosensitive cathode is placed so as to collect the maximum amount of light radiated by the crystal. The cathode is a layer of suitable photosensitive material deposited on a solid electrode within the envelope. The electrode structure of the photomultiplier takes a variety of shapes. The photoelectrons from the cathode are accelerated by the applied field to the first dynode. On striking this they release secondary electrons which in turn are drawn to the second dynode and so on until a pulse of electrons is collected at the plate. The dynode surface is so processed that about three to five slow secondary electrons are emitted for each insident fast electron. Commercial tubes generally have between ten and fourteen stages. Thus a magnified avalanche

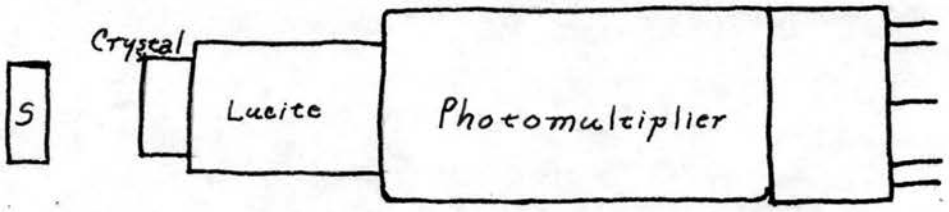

Figure 6. Scintillation counter arrangement.[18]

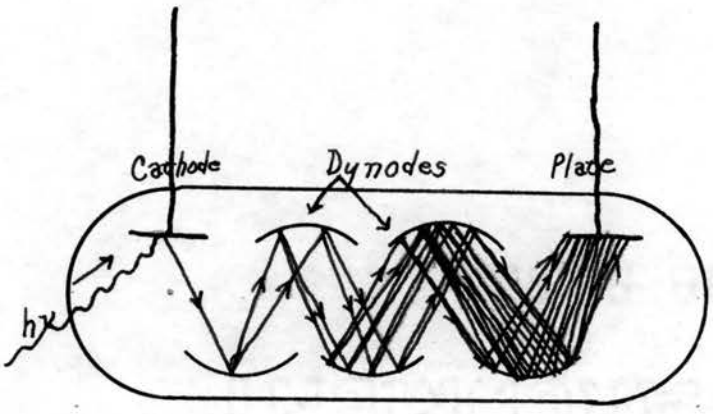

Figure 7. A photomultiplier tube.[19]

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[18]Ibid., p. 238

[19]Ibid.

of electrons arrives at the plate. The output voltage developed between plate and ground by a current passing through, may be amplified by an external electronic amplifier or measured without external amplification by applying it to the deflecting system of a cathode ray tube or to a current meter of some kind.

For spectrometry the number of fluorescent quanta emitted should be proportional to the energy expended by the particles or photons incident upon the material. Also the number of photoelectrons released by the fluorescent quanta should be directly proportional to the expended energy.[20] The output of a photomultiplier can be fed into a battery of discriminator circuits, each containing an electron tube biased so that it will not respond to pulses below a desired size but will count all larger pulses. This can be used to identify particles.[21]

An antimony-caesium photocathode is the best now known. It has large absorption of incident quanta and a low work function.[22]

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[20]C. Curran, Luminescence and the Scintillation Counter (London, 1953), pp. 1-7.

[21]Lapp and Andrews , p. 239.

[22]Curran, p. 55.

CHAPTER IV

SOME PROJECTS FOR HIGH SCHOOLS

The projects in this area suitable for use in high schools are limited by considerations of safety, expense, and skill at building equipment. Radioactive sources with activities of a few microcuries are harmless, as long as the radioactive substance is not taken into the body. Such sources may be used in schools if the detecting and measuring equipment is of sufficient sensitivity.[1] Such equipment as spectroscopes, x-rays tubes, Geiger-Muller Counters, scintillation counters, etc. are expensive and are not usually found in high school laboratories. Therefore, projects are limited by the equipment available or the expense a student is willing and able to afford for them. The expense can be reduced if the student can build his own equipment, but this is limited by his skill.

With these factors in mind the following projects are suggested as ones that interested high school students can do and possible can afford.

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[1]M. C. Nokes, Radioactivity Measuring Instruments, (New York, 1958) p. 3.

Photographic Projects

1. Photographic films of various speeds may be exposed to the same amount of radiation of one kind and the results compared. The films can be ranked in the order of response to the radiation. This can be done for ultraviolet light if a spectrometer with quartz prism is available to separate the ultraviolet rays from a commercial lamp into different wavelengths. A part of each film should be protected from the radiation so that it will act as a control for comparison purposes.

The mixture of ultraviolet light of different wavelengths can be used. In this case a small strip of each film can be mounted on a plate and all of them exposed at once. After this plate is developed comparison will show which has the best response, etc.

This can be repeated with x-rays if an x-ray tube is available. It can also be done with gamma-rays if a gamma emitter is available. In all cases the film needs to be protected from all radiations except those from the source which is planned for the experiment.

2. Radioisotopes may be detected in plants and animals which have been treated with compounds containing radioactive phosphorus by firmly pressing the leaf, stem, skeleton, etc., against the film for the desired length of exposure time. The film must be covered with black paper.[2]

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[2]Samuel Schenberg, ed., Laboratory Experiments with Radioisotopes for High School Science Demonstrations (Washington, 1953), pp. 33-36.

Projects with the Electrostatic Dosimeter

1. The building and demonstration of an electrostatic dosimeter is a project that is well within the ability of most high school physics students.

The electroscope may be made with rectangular pieces of glass, masking tape, conducting rod and gold foil. On one of the sides mark off a scale so that the reading will be zero when the electroscope is charged and at maximum reading when fully discharged.

2. Doses from different sources can be compared by using this device. Charge the electroscope. Bring a radioactive source to a specified distance from the knob of the electroscope and time the discharge. Repeat with the other sources and compare the times of discharge.

3. The inverse square law for gamma rays may be tested with this dosimeter. Bring the source of rays three inches from the electroscope knob and time the rate of discharge. Recharge the electroscope and bring the source six inches from the electroscope knob and time the rate of discharge again. This may be repeated for other distances. Compare the times of discharge for the various distances.

These projects may be demonstrated to large groups by printing the scales upside down and backwards. Then, by shining a light through the electroscope and a large lens, the image can be projected onto a screen.[3]

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[3] Nuclear Science in the Classroom, A Handbook for Teachers, The Dept. of Public Instruction, Bulletin No. 362 (Lansing, Michigan, 1957), pp. 12-13.

Projects with Cloud Chambers

1. A cloud chamber of the Wilson type can be constructed rather simply. Cut two holes in a 125 ml. Erlenmeyer flask, one on each side. Insert a small nail through each of two stoppers for electrical leads. Mount a pin with a speck of radioactive material on one stopper and insert both stoppers into the flask. Fill the flask over half full with a mixture of alcohol and ink. Put a rubber bulb over the mouth of the flask and connect the voltage source to the field leads. The chamber may be mounted on a ringstand and adjusted to a light source.[4]

2. A continuous cloud chamber can be made rather simply also. Take a screw-cap jar about three by three inches. Cut a circle of black felt to fit in the cap of the jar. Cut another circle of felt to fit the bottom of the inside of the jar. Shape an iron wire retainer to hold the circle of felt in the bottom of the jar when it is inverted. Pour enough methyl alcohol into the jar to saturate both felts. Tighten the cap and set the jar, cap down, on a cake of dry ice. Adjust a spotlight to a sloping angle.[5]

3. Either of these cloud chambers may be used to detect secondary cosmic rays. The continuous chamber needs only to be watched. The other one must be expanded before the tracks will show. By rigging up a scale as near to the sensitive

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[4]Ibid., p. 49.

[5]Schenberg, p. 15.

volume as possible one can determine the approximate length of some of the tracks.

4. The energies of alpha and beta particles and gamma rays from various sources may be compared by the use of these chambers. Place a radium source mounted on a pin in the sensitive volume of the cloud chamber. It is necessary to place alpha and beta sources inside the chamber because the glass absorbs these particles. Place a ruler just behind the chamber. Observe the width and length of the tracks of the alpha particles as accurately as possible. Substitute other sources of alpha particles and note the width and length of the tracks. Compare the size of the tracks in a graph or table. Repeat, using sources of beta particles. Repeat, using sources of gamma rays. The gamma sources will work well if placed external to the chamber.

5. Focus the x-rays, if a tube is available, on the chamber and observe any tracks. Shine an ultraviolet light on the chamber and observe any tracks. For this a quartz window is needed in the chamber.

Projects with a Geiger Counter

1. A Geiger counter may be constructed which is useful in the detection of alpha, beta, or gamma rays. It should be wired according to the following schematic diagram.

2. First, determine the background radiation by counting the clicks in the earphones for several minutes and taking the mean. Then determine the activity of various radioactive

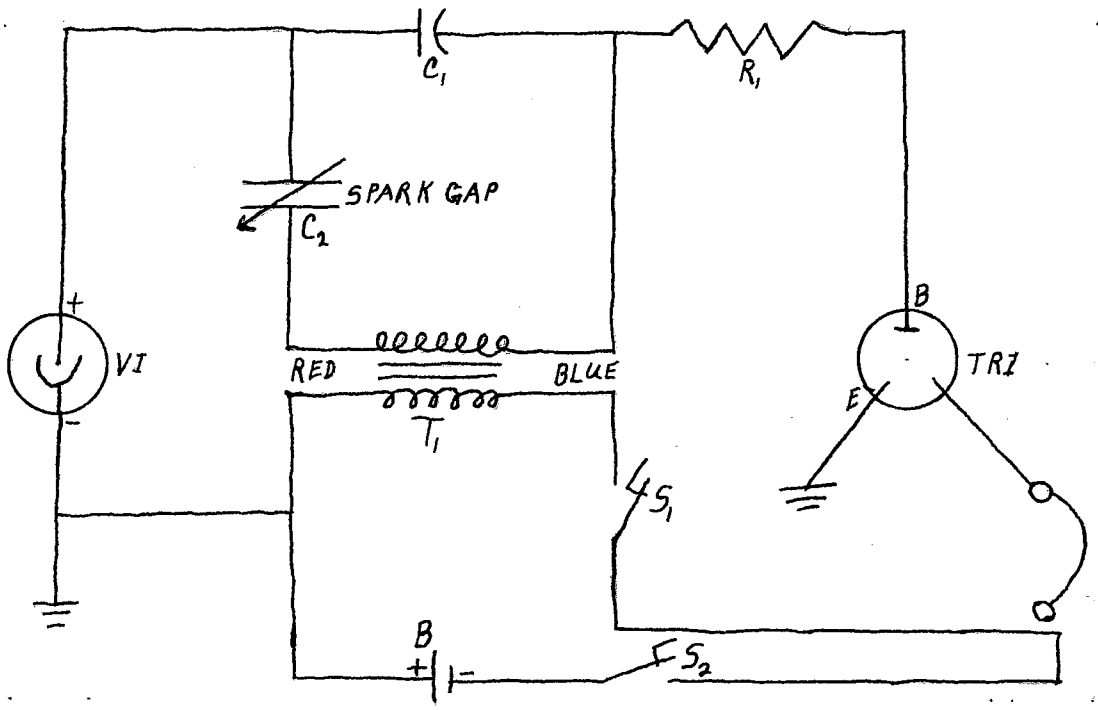

Figure 8. Schematic diagram of a Geiger counter.

B : 1½ volt flashlight batteries
C_1 : .05 mfd., 1000 volt capacitor, plastic sealed
R_1 : 1 megohm ½ watt resistor
S_1 : S.P.S.T. snap action spring return switch
T_1 : small audio output transformer such as 4000 ohms to 4 ohm voice coil
C_2 : gap-altered 3-30 mfd. trimmer capacitor
TRI : CK722 pnp junction transistor
VI : Geiger counter tube Victoreen 1B85 or Raytheon CK1026
S_2 : S.P.S.T. Toggle switch

high impedance head phones
wire
solder
terminal strip
phone jack
3" x 4" x 5" metal cabinet[6]

For further information on this counter see Popular Electronics, June 1956, pp. 90-93.

For wiring diagrams of more elaborate Geiger counters see M. D. Nokes, Radioactivity Measuring Instruments, New York: Philosophical Library, 1958.

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[6]Nuclear Science in the Classroom, A Handbook for Teachers p. 86.

sources by bringing the Geiger tube to a certain specified distance from the source and count the clicks for several minutes and take the mean. The difference is the activity in counts per minute.

3. Starting at zero voltage plot the activity in counts per minute against the voltage. For this a continuously variable voltage supply is needed. Determine the Geiger threshold; i. e., the voltage at which all ionizing events produce approximately the same size pulse of current.

CHAPTER V

SUMMARY

The problems of detection and identification of radiant energy and emitted particles arise because the photons and particles are invisible. Detection depends on the effects which these photons and particles have on matter. The principal effects are excitation and ionization of atoms. The ionization can be detected and measured by various devices such as electroscopes, cloud chambers, ionization chambers, proportional counters, and Geiger-Muller counters. When electrons return to their ground level in some atoms, flashes of light are given off. This is used in scintillation counters. Ionization produces permanent chemical changes in some substances. This is used in photographic devices. Some excitation raises the temperature or produces electric current. This is used in bolometers and thermopiles.

Any project is recommended for high school which involves low enough activity to be fairly safe. In particular the building and use of cloud chambers and Geiger counters is recommended. Photographic detection is also recommended.

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