CHAPTER I

PHYSICS OF RADIATION

A. GENERAL STATEMENTS

(1) Radiation travels through empty space. From the studies of radiant energy have come several ideas about its nature. For one thing, it is known that such energy is propagated through empty space. Moreover, it is the only form of energy known which can flow through matter-free space. The vast amounts of solar radiation which maintain the earth at such a temperature that life is possible, come from the sun through millions of miles of interstellar space, which contains but an infinitesmal density of matter.

(2) Radiation energy spectrum. Radiation occurs over an extended energy range. The extremely high-energy *gamma* rays penetrate several inches of lead; the lower-energy *x-rays* pass through perhaps an eighth of an inch of lead; *visible light* is absorbed by a metal layer only a few atoms thick; and, finally, *radio waves* are completely absorbed by a coarsely-woven copper wire screen. The character of radiation varies greatly, as one can see, from one part of the radiant energy spectrum to another.

(3) Radiant energy travels through space with a fixed, definite velocity. Radiant energy might be given the alias of traveling energy, for it spends each instant of its existence traveling through space at its particular speed of 3×10^{10} cm. per second (speaking here of space in which the matter density is zero). This speed is entirely independent of the character of the radiation. To the best of our knowledge, radio waves, visible light and gamma rays all travel with precisely this velocity. The direction of travel is rectilinear.

(4) Radiation exhibits the phenomena of interference. Any form of wave motion can be made to exhibit the

phenomena of interference. The beats heard when two tuning forks of nearly the same frequency are struck, are an example. Later (see p. 128), an example of interference exhibited by light will be given.

(5) Radiation may be observed when, and only when, it is allowed to interact with matter. This statement is a reminder that all recognized measurements of energy are limited to energy associated with matter. To detect or measure radiant energy, it is necessary that it be transferred into the familiar potential or kinetic energy of matter. This transformation obeys the law of conservation of energy, i. e. the number of ergs of radiant energy disappearing is equal to the number of ergs of potential or kinetic energy which appear.

B. PHENOMENA OBSERVED UPON THE INTERACTION OF RADIATION AND MATTER

(1) Reflection. Radiant energy may be regularly reflected from a plane surface whose granular structure is small in comparison with the wave length of the radiation. In this case the angle of reflection is equal to the angle of incidence, and the reflected energy is in the plane of the incident energy. No perfect reflectors of radiation are known; thus, always some of the radiation is transmitted or absorbed by the reflector.

(2) Absorption. Matter never fails to take its toll from the radiation incident upon it. No material substance known is totally transparent to radiant energy. The mechanism of absorption will be treated later (see p. 16).

(3) Refraction. Matter has the property of changing the velocity of energy which is passing through it. This results in a change of direction of the radiation (see fig. 1). The ratio of the velocity of radiation in matter to the velocity in space is called the index of refraction of the refracting substance.

(4) Dispersion. The phenomenon of dispersion occurs because the index of refraction of any transparent material depends also upon the wave length of the radiant energy which is passing through it. A beam of white light is dispersed into a colored band or spectrum when passed through a prism since each wave length suffers a different refraction (see figs. 2a and b; also see p. 18).

These are only a few of the many phenomena which characterize radiant energy in its passage through space and matter; these must be explained by any theory of radiation. The question: *What is the nature of radiant energy?* has been nearly answered by each of two different theories, the wave theory and the quantum theory. As it will be pointed out later, it seems not impossible to effect a harmonious combination of these two into one which adequately covers all the observed phenomena of radiant energy.

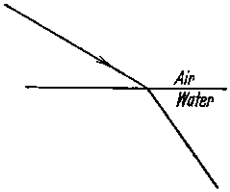


Figure 1. Refraction.

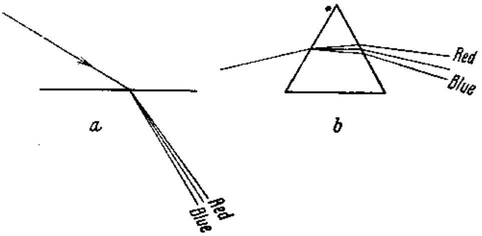


Figure 2. Refraction and Dispersion.

The so-called "mitogenetic radiation" which is the principal subject of this book is said to proceed rectilinearly, and to show reflection, absorption, refraction and dispersion, as will be demonstrated in Chapter IV. If so, it is a true radiation.

C. THE WAVE THEORY OF RADIANT ENERGY

There are three ways in which energy may be transferred with the aid of matter, namely (1) by the flow or movement of definite masses of matter, such as tides in the seas, or the drive rod on a locomotive; (2) by wave motions in elastic media, such as sound in air; and (3) by material projectiles. The wave theory of radiation is based upon the well understood principles of wave motions in elastic solids. These may be illustrated by the following simple experiments.

If a long stretched rope is given a blow at one of its supports, a rather surprising thing happens (at least so to the uninitiated); a hump in the rope is seen to speed along it. If, for a short period of time this end of the rope is given a regular to-and-fro motion, a disturbance as pictured in fig. 3 will travel along it with the same velocity as in the former case. This sort of disturbance is called a wave train. The length of the individual waves, or the wave length, λ, is the distance from crest to crest or trough to trough. The frequency, ν, or the number of waves passing a fixed point per second, is equal to the velocity, c, divided by the wave length:

Figure 3.
A short wave train in a rope.

$$\nu = \frac{c}{\lambda}.$$

Reflection. Let this wave train be observed when it reaches the end of the rope. If the support there is ideally rigid, the train of waves will be reflected and will travel back along the rope with the same velocity and amplitude it had before reflection.

Absorption. If the support is ideally non-rigid, the wave train will set it in motion, spend its energy upon it and completely disappear. In this event, the energy carried by the wave train has been transferred to the support.

Standing Waves. There is still another phenomenon of wave motion which may be illustrated by waves in the rope. When it is fastened to the rigid support, if the free end is kept moving with a uniform to-and-fro motion, so-called standing waves will be formed (see fig. 4). The rope appears to be divided into vibrating segments called *loops* which are separated by points of little or no motion called *nodes*. These standing waves, not true waves at all, are the result of the interference of the original

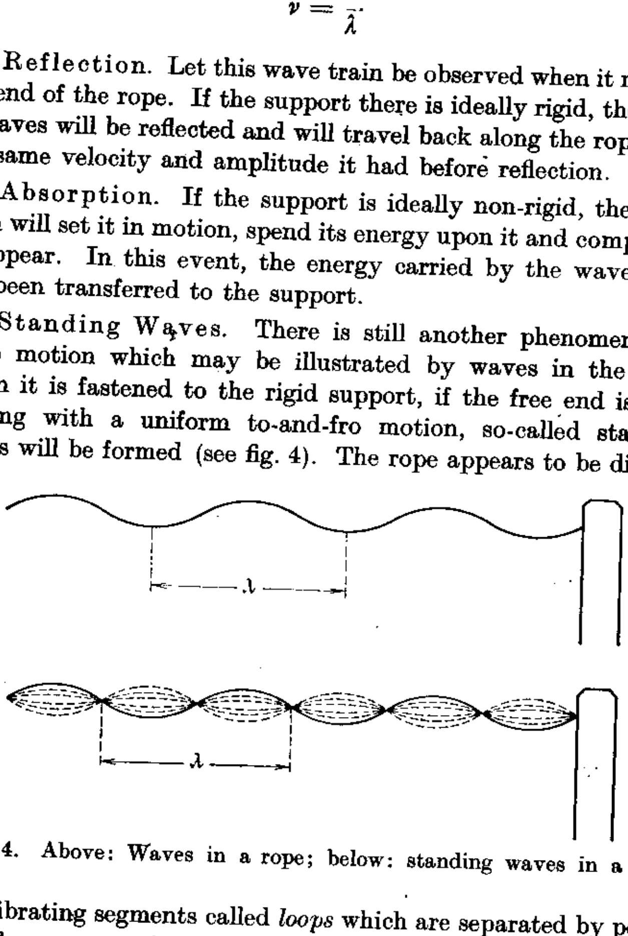


Figure 4. Above: Waves in a rope; below: standing waves in a rope.

and the reflected waves. Their importance lies in the fact that they offer a very simple way of determining the wave length of the true waves which is equal to twice the distance between nodes.

Suppose a system of ropes is strung from a central point so they lie in a plane (see fig. 5). If the central point is given a regular up-and-down motion, waves will travel out along each rope and the system will present somewhat the appearance of still water into which a stone has been dropped. The wave trains traveling outward along each rope with the same velocity give the appearance of regularly growing or spreading concentric rings. The rings are separated by a distance equal to the length of the waves. If more ropes are added to this system so that they are stretched equally in every direction in various planes and the central point is given a regular to-and-fro motion the system will give the appearance of expanding or growing spherical shells. Here the distance between the shells is again equal to the length of the waves in the individual ropes. The mechanical rope apparatus is frequently used as an analogy to the electric field of a point charge.

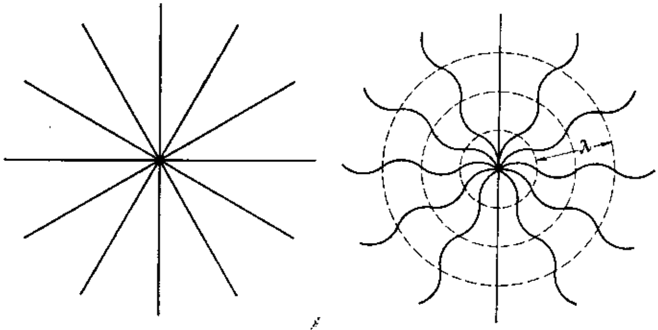


Figure 5. Radiation from a central point.
left: a rope system; right: waves in a rope system.

Definition of a Charge of Electricity. Electricity, according to present ideas, embodies two kinds called positive and negative. If an object has equal amounts of the two, it is said to be electrically neutral. If it has an excess of either kind it is said to be charged, and this excess is called an electric charge. Usually this charge is distributed over the surface of the object.

In discussions of the effects of one charge upon another, and in related problems, it is convenient to ignore the object and to think of the charge as being concentrated at one point. This is called a point charge.

The Electric Field of a Point Charge. We will now see why the three-dimensional system of ropes forms a rough mechanical analogy to the electric field of a point charge. Suppose a charge of positive electricity is fixed in space at some point A. If a charge of negative electricity is brought to some point B, it will experience a force which tends to draw it straight toward A as though the two were connected by an invisible stretched elastic cord. The point B may be anywhere in space in the vicinity of A and still it is drawn directly toward A. We may then think, if we like, of the space about A as filled or made up of these stretched elastic cords (called lines of force) extending outward in every direction from the charge at point A.

Now, if the charge at A were given a rapid to-and-fro motion, it would seem likely that waves should be formed and sped along the lines of force through space. This is the explanation offered by the wave theory of light concerning the manner in which radiant energy is propagated through space. We know that electric fields surround electric charges. Radiation is associated with waves traveling through these fields.

The waves in the electric field about the charge which has been set in oscillation are known to be not the only waves present. In fig. 3 is represented the shape of one of the lines of force shortly after the charge has been given a few oscillations. The train of waves which consists in variations in the direction of the line of force is traveling along this line with the velocity of light. Now it is known that the motion of an electric field through space produces an associated magnetic field. It therefore follows that this wave train must have associated with it a train of waves of magnetic intensity. These two wave trains lie in planes perpendicular to each other. The classical electromagnetic wave along one line of force is represented in fig. 6. Radiation is then nothing other than these electromagnetic waves.

The wave theory predicts that the velocity of propagation of these waves should be independent of their wave length. Moreover, such waves would be expected to exhibit all the phenomena of interference just as radiation does.

An oscillating charge radiates energy, of course, not only along one line of force but in all directions, though the amount of radiant energy sent out in different directions varies. Zero energy is radiated along the line of motion of the charge and the maximum amount is radiated in a plane normal to the direction of motion.

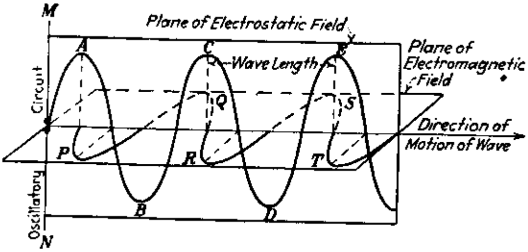
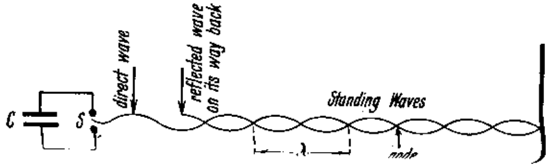


Figure 6. Diagram of an electromagnetic wave.

HERTZ (1866) caused a charge to oscillate rapidly between two closely-placed points¹) and found that energy was being radiated as the result of the accelérations of the charge (see fig. 7). He placed a metal plane some distance from the oscillating charge



and found regularly-spaced points between the radiating charge and the reflector at which the energy was alternately of a maximum and of a minimum value. These loops and nodes showed that the energy was being radiated in the form of transverse waves, the direct and the reflected beam interfering to cause standing waves.

When the velocity of these waves, which are of the wave length of short radio waves, was found to equal the experimentally-determined velocity of light, it was immediately suggested that light was nothing other than such waves, only of shorter wave length.

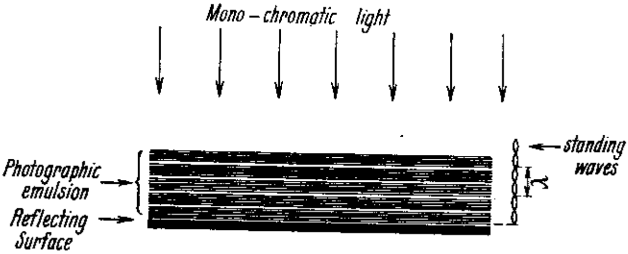


Figure 8. Experiment showing the wave nature of light.

A simple experiment performed by LIPPMANN showed that visible light could be made to form standing waves and thus must have a wavelike nature. Light of one wave length was allowed to shine perpendicularly upon a fine-grained photographic emulsion which was backed by a reflecting layer of metallic silver. When the emulsion was developed, cut and the edge viewed under a microscope (see fig. 8) alternate exposed and unexposed layers were found to exist throughout the depth of the emulsion. At planes where the direct and reflected beams interfered to form the nodes of the standing

cm. of *surface placed normal to the radiation at that* point (see and found regularly-spaced points between the radiating charge and the reflector at which the energy was alternately of a maximum and of a minimum value. These loops and nodes showed that the energy was being radiated in the form of transverse waves, the direct and the reflected beam interfering to cause standing waves.

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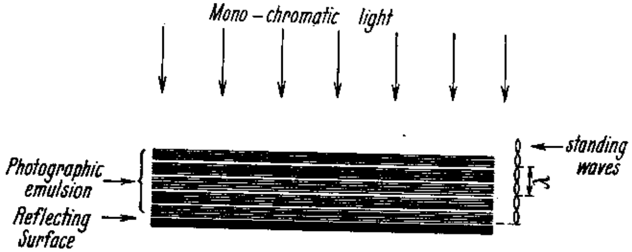

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Definition of Intensity. The intensity of radiation received from a source at a fixed point in space is defined as being the number of energy units (ergs) received per second by a square cm. of surface placed normal to the radiation at that point (see

9a). When the radiation is strictly parallel, the intensity per m^2 will be the same at any distance from the source (fig. 9a). With a point source, it will decrease as the second power of the distance between the radiating source and the point of measurement. Thus, in fig. 9b, A will receive K ergs per second while B, twice as far from the source, receives only $\frac{K}{4}$ ergs. In practice, point surfaces are rare, radiation generally being emitted by surfaces or volumes. (This is commonly the rule in biological radiations.) For these cases, the inverse square law holds only for distances so great that the source may be considered to be a point. For shorter distances the intensity may be roughly proportional to the reciprocal of the distance; for points still closer to the source, the intensity may be independent of the distance. Experiment is the best means of determining the variation of intensity with distance in the region of space closely surrounding a source of finite size.

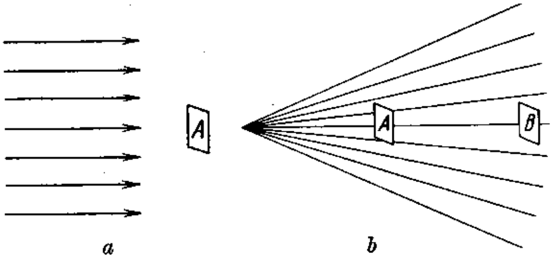


Figure 9. Illustration of the definition of intensity.

The wave theory of radiation has been successful in explaining how radiant energy may be transferred through space; it has predicted accurately the velocity of radiant energy; the phenomena of interference, reflection, refraction, dispersion, polarization and double refraction offer no difficulties; however, with respect to the emission and absorption of radiant energy, the classical theory fails and gives place to the quantum theory.

D. THE QUANTUM THEORY OF RADIATION

1. Definitions. It is known that matter exhibits the curious behavior of *discontinuity* in processes in which it emits or absorbs radiant energy. A given atom, for example, will

convert, of its store of energy, only certain multiples of the unit of energy into radiation. Likewise, it will absorb radiant energy only when the energy comes in precisely the proper-sized amounts. This phenomenon is one with which the wave theory of light is unable to cope.

Let us lay aside for the moment then, this conception of the nature of radiation and consider the only other possible one, i. e. that radiation is corpuscular in nature. Thus we think now of radiation as consisting of small energy projectiles which travel through space with the familiar velocity of 3×10^{10} cm. per second. These projectiles are of course non-material; they consist simply of small units of energy.

Since we have seen that the different kinds of radiation, from radio waves to gamma rays, all travel with the same speed, these differences can occur only by differences in the size of each projectile, or quantum. It has been shown that the energy of a quantum can be given as the product of a universal constant, h, known as PLANCK's constant and equal to 6.55×10^{-27} erg seconds, and the frequency of the equivalent electromagnetic wave. Energy of quantum $E = h\nu$.

In Table 1, column I are given the various wave lengths in ÅNGSTROM units ($1\,\text{Å} = 10^{-10}$ m). Column II gives the corresponding frequencies obtained from the equation

$$\nu = \frac{c}{\lambda},$$

where c is the velocity of light. In the third column are the quantum energies, E, which correspond to each frequency ($E = h\nu$). Thus, an X-ray quantum is a 10^{-8} erg projectile, while a quantum of visible light has an energy value of but 10^{-12} ergs, and those of the ultraviolet being about 2 to 10 times as large as those of visible light.

For the understanding of emission and absorption of quanta by matter, it is necessary to discuss briefly the atomic theory.

2. Atomic Theory. Let us suppose (see fig. 10) that an electron is held at some distance, r, from a small positively-charged particle, q. From our knowledge of electrostatics we know that the electron experiences a force of attraction toward q. This force, F, is proportional to the number of units of charge possessed

	Wave Length in Å	$\nu = c/\lambda$ Frequency	Energy of Quantum $E = h\nu$ (in ergs)	Electron Energy $V = \frac{12336}{\lambda}$ (in volts)
gamma rays	0.001	2.998×10^{21}	1.96×10^{-5}	1.23×10^{7}
	0.01	2.998×10^{20}	1.96×10^{-6}	1.23×10^{6}
x-rays	0.1	2.998×10^{19}	1.96×10^{-7}	1.23×10^{5}
	0.3	9.993×10^{18}	6.54×10^{-8}	4.11×10^{4}
	0.5	5.996×10^{18}	3.93×10^{-8}	2.47×10^{4}
	1.0	2.998×10^{18}	1.96×10^{-8}	1.23×10^{4}
	10.0	2.998×10^{17}	1.96×10^{-9}	1.23×10^{3}
ultraviolet	100.0	2.998×10^{16}	1.96×10^{-10}	1.23×10^{2}
	1000.0	2.998×10^{15}	1.96×10^{-11}	1.23×10^{1}
	1850 (Hg)	1.621×10^{15}	1.06×10^{-11}	6.67
	2000	1.499×10^{15}	9.81×10^{-12}	6.17
	2500	1.199×10^{15}	7.85×10^{-12}	4.93
	2536 (Hg)	1.182×10^{15}	7.74×10^{-12}	4.86
	2700 (Hg)	1.110×10^{15}	7.27×10^{-12}	4.57
	3342 (Hg)	8.971×10^{14}	5.87×10^{-12}	3.69
	3656 (Hg)	8.200×10^{14}	5.37×10^{-12}	3.37
visible light	4350 (Hg)	6.892×10^{14}	4.51×10^{-12}	2.84
	5000	5.996×10^{14}	3.93×10^{-12}	2.47
	5500	5.451×10^{14}	3.57×10^{-12}	2.24
	6000	4.997×10^{14}	3.27×10^{-12}	2.06
	6500	4.612×10^{14}	3.02×10^{-12}	1.90
	7000	4.283×10^{14}	2.80×10^{-12}	1.76
heat waves.	8000	3.747×10^{14}	2.45×10^{-12}	1.54
	10000	2.998×10^{14}	1.96×10^{-12}	1.23
	20000	1.499×10^{14}	0.98×10^{-12}	0.62
radio waves	10 cm to 600 m			

by q and is inversely proportional to the square of the distance, r, or

$$F = \frac{q}{r^2}.$$

Let us assume that q is heavy compared to the electron so that the electron will be the motile one of the two charges. If the electron is released from its position, it will, of course, fall toward and into the positively-charged body, q. Suppose, however, that the electron is set travelling in a circular orbit about q as the center (see fig. 11). If its orbital velocity is adjusted until its centripetal force is just equal to the force of attraction, F, exerted upon it by q, then the electron will be in stable equilibrium remaining indefinitely in this orbit.

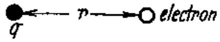


Figure 10.
Positive and negative charges at the distance r from each other.

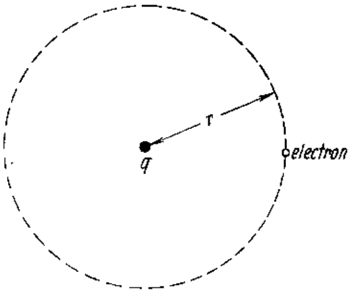


Figure 11.
Electron in a circular orbit traveling about the positive charge q.

An example of such a system is furnished by the sun and the earth. Here it is the balance between the earth's centripetal force due to its orbital velocity and the gravitational atraction of the sun which keeps the earth in its orbit.

If the mass of q is 1.65×10^{-24} grams, the distance r is 0.5×10^{-8} cm. and the charge q represents an electron, then fig. 11 represents a hydrogen atom. q, which is thus the unit of positive electricity, becomes the nucleus of the atom and the electron represents the hydrogen atom's one orbital electron.

From elementary considerations it would seem that the nucleus with its orbital electron would form a stable system also for values of r other than 0.5×10^{-8} cm. For any value of r, a corresponding orbital velocity can be calculated which will bring about the balance of the electrostatic attraction and the centripetal force of the electron. However, it is found experimentally that there are only a few orbits, out of the infinite number possible, which the orbital electron frequents. From the radius, r_1, of the innermost orbit of H which we have just seen to be equal to 0.5×10^{-8} cm. we may calculate the other possible orbits by the relation

$$r = n^2 r_1$$

where n has any value 1, 2, 3, 4 . . . . . .
The orbital velocity of the electron decreases as n increases, and the limiting case $n \rightarrow \infty$ corresponds to an atom with its electron at rest at an infinite distance from the nucleus.

The energy possessed by the atom or the nucleus-electron system, for the case when the electron is in any one particular orbit, can be easily calculated and this energy characterizes the *energy state* of the atom. The atom has the least energy when the electron is in the innermost orbit (state of least energy) and its energy increases as the electron exists in orbits of greater radius (states of higher energy). The innermost orbit is the preferred one, i. e. the electron inhabits this one the greater part of the time. In this case, the atom is said to be in its *normal* state. The usually unoccupied orbits are called *virtual orbits.* We have seen that the hydrogen atom can exist in different energy states, and we will very shortly apply this idea in a discussion of the absorption and emission of radiant energy by atoms (see pp. 14 and 16).

Before considering these topics, it will be advantageous to see how other atoms beside hydrogen are constituted. The one next in simplicity is helium. Its nucleus consists of 4 simple hydrogen nuclei, called protons, and 2 electrons. Two orbital electrons complete the atom. In all atoms, the number of protons in the nucleus exceeds the number of electrons by just the number of orbital electrons; this leaves the nucleus with a positive charge and the whole atom electrically neutral. For example, the carbon atom is composed of a nucleus of 12 protons and 6 electrons about which revolve 6 electrons in the various shells. The oxygen atom consists of 8 outer electrons and a nucleus which contains 16 protons and 8 electrons. The atomic weight of carbon is approximately 12 and that of oxygen is 16. It can be seen that the atomic weight is equal, for all practical purposes, to the number of protons in the nucleus of the atom. The atomic number is equal either to the number of nuclear or orbital electrons. Table 2 shows in what way the outer electrons group themselves in the orbital shells for the first eleven elements of the periodic table.

Table 2. Electron Configuration for the Elements from H to Na.

Element	Atomic Number	*K* shell	*L* shell	*M* shell
H	1	1		
He	2	2		
Li	3	2	1	
Be	4	2	2	
B	5	2	2 1	
C	6	2	2 2	
N	7	2	2 3	
O	8	2	2 4	
F	9	2	2 5	
Ne	10	2	2 6	
Na	11	2	2 6	1

Fig. 12 is a wholly diagrammatic representation of the *Na* atom. The central dot marks the nucleus; the first circle is called the *K* shell and contains two electrons. The binding energy of these negative charges is about 1000 electron volts or 1.6×10^{-9} ergs; this amount of energy would be required to remove either one of the *K* electrons from the atom. The next circle representsthe *L* orbit, which in *Na* contains 8 electrons, the binding energies of which are approximately 35 electron volts. In the last solid circle there is but one electron and its binding energy is about 5 electron volts. The outer dotted circles represent energy levels which are unoccupied in the normal *Na* atom, i. e. virtual orbits.

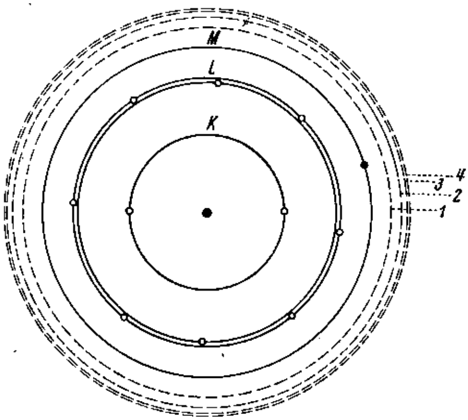


Figure 12. Diagram of the sodium atom showing the various shells.

3. The Emission and Absorption of Radiation by Atoms. We have seen that the hydrogen atom can exist in various energy states associated with the orbit occupied by its electron.

By this necessary mechanism can be explained the absorption and emission of radiation. If the atom changes from an energy state E_m to a lower one E_n, it does so with the emission of a quantum of radiant energy *hν* such that

$$h\nu = E_m - E_n. \tag{1}$$

If the atom changes from an energy state E_n to a higher state of energy E_m, it can do so only by the absorption of a quantum of radiation *hν* of such energy value that

$$h\nu = E_m - E_n. \tag{1}$$

In this equation *h* is the universal constant known as PLANCK's constant equalling 6.547×10^{-27} erg. secs. and *ν* is the frequency (see p. 4). It follows that the various quanta *hν* may be emitted and absorbed by the hydrogen atom.

$$\begin{aligned} h\nu &= E_m - E_0 \text{ where } m = 1, 2, 3 \ldots\ldots \\ h\nu &= E_m - E_1 \quad ,, \quad m = 2, 3, 4 \ldots\ldots \\ h\nu &= E_m - E_2 \quad ,, \quad m = 3, 4, 5 \ldots\ldots \\ h\nu &= E_{n+1} - E_n. \end{aligned}$$

Since $\lambda = \frac{c}{\nu}$, where *c* is a constant which is equal to the speed of light or 2.99796×10^{10} cm. per sec., the wave length of the radiation resulting from or producing the energy change $E_m - E_n$ in the atom will be given by the equation

$$\lambda = \frac{ch}{E_m - E_n}$$

Table 3 gives the values of the first eight of the forty or so known energy states of the hydrogen atom.

Table 3. Energy obtained by electron shifts from normal to higher orbits in the Hydrogen atom

number of virtual orbit	E in ergs × 10^{-12}	corresponding wave length in Å
0	0	0
1	16.14	1216
2	19.15	1025
3	20.18	975
4	20.70	948
5	20.90	940
6	21.05	933
7	21.16	928

The wave length emitted by the hydrogen atom for the energy change $E_1—E_0$ for example, is readily calculated from the data in this table, as

$$\lambda = \frac{2.99796 \times 10^{10} \times 6{,}547 \times 10^{-27}}{161.4 \times 10^{-\text{[illegible]}} - 0} =$$

$$1216 \times 10^{-8} \text{ cm. or } \lambda = 1216 \text{ Å}.$$

This wave length is in the far ultraviolet. Changes between other states result in the radiation of visible light and still others produce radiation in the far infra red, e. g. for the shift from the 6th to the 7th orbit, it is 178 500 Å.

The equation (1) states that an atom in the state E_n will absorb a quantum $h\nu$ and be raised to the energy state E_m if the quantum is precisely equal to the difference in the energy of the two states. Supposing the energy of the quantum is slightly less than this difference—will it be absorbed? The answer is no; there is no possibility that it will be. If the quantum is larger than $E_m—E_n$, then it may be absorbed. It will be, of course, if its energy happens to equal the energy difference between any two states provided that, at this moment, the electron is in the orbit corresponding to the lower of these states. If its energy is not one of these discrete values, it will not be absorbed — *unless* its energy is greater than $(E_\infty — E_n)$, i. e. sufficient to shift the electron beyond the outermost orbit. In this event, it may be absorbed and the surplus, $h\nu—(E_\infty — E_n)$, is used in shooting the electron away from the atom, or

$$h\nu = E_\infty - E_n + \frac{1}{2} mv^2$$

where m is the mass of the electron and v is its velocity (the term $\frac{1}{2} mv^2$ represents the kinetic energy of the ejected electron). An electron so ejected from an atom is called a *photoelectron*, and the atom itself is said to be *ionized*.

As has been stated before, an electron spends most of its existence in the normal state, E_0. When it has been raised to a state of higher energy E_n by virtue of the absorption of energy, the atom is said to be in an *excited* state. The life of an atom in an excited state is of the order of 10^{-7} to 10^{-9} seconds. After this length of time the atom reverts to its normal state with the resulting emission of radiant energy.

These remarks on emission and absorption of radiation apply not only to hydrogen but to the other atoms as well. Only the outer electrons of the more complicated atoms behave in a manner similar to the one electron of hydrogen. In this way originate the atomic spectra. They are emitted by sources (such as the mercury arc or a glow discharge tube) in which the gas is at sufficiently low pressure that the atoms are not in contact with each other but for a small fraction of the time. If the pressure is raised (also the case for solids), a *continuous* spectrum is emitted which does not contain lines characteristic of the atom. This is called *thermal* radiation since it is the result of the temperature of the source. The atoms are so close together that the outer virtual orbits intermingle and are distorted.

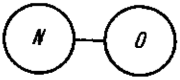
These last remarks apply equally well to absorption. An element in the gaseous state will give a line absorption spectrum, while in the solid state it will give continous absorption.

Molecular Spectra

While atomic radiation results from electrons jumping from one energy level to another, molecular spectra are assumed to arise from the motions of atoms or, better, ions which form the molecule.

Let fig. 13 represent a simple diatomic molecule such as NO. Such a molecule emits radiation in three wave length regions: (1) the far infra red; (2) the near infra red; and (3) the visible or the ultraviolet regions. The radiation in the first group is ascribed, in the simple theory, to changes in the rotational energy of the dipole molecule. The second group is ascribed to simultaneous changes of rotational and vibrational energy, and the third, to simultaneous changes in rotational, vibrational and electronic energy of the molecule.

Figure 13.
A simple diatomic molecule.



Molecular spectra are in general exceedingly more complex than atomic spectra. The great number of lines fall into groups which under low dispersion give the appearance of bands.

The absorption spectrum of a molecule is, of course, its emission spectrum in reverse, light bands replaced by dark.

In this connection, the effect of radiation upon chemical reactions should be mentioned. To realize that such an effect does exist, it is only necessary to remember the number of brown bottles that are used for storing chemicals. The most prominent effect is that of light on silver salts as in all photographic emulsions. The result is the reduction of the salt with the deposition of metallic silver. Without presenting the theory of the process, it is still easy to see that the absorption of radiant energy might do just this. For an absorption of energy means that the molecule must go into a state of higher energy-a less stable state- and this may, on the absorption of sufficient energy, become a chemically unstable state.

E. ANALYSIS OF RADIATION BY DISPERSION INTO A SPECTRUM

The radiation emitted by a source is characterized by the wave lengths present, together with the distribution of energy among these wave lengths. A given atom will emit only certain lines (its line spectrum) and each one will have associated with it a certain energy (see upper spectrum of fig. 14); a molecule may give rise to some such spectrum as that of the center strip, and an incandescent solid emits all wave lengths with varying intensity beyond a certain wave length, depending upon the temperature of the solid (see lower spectrum of fig. 14).

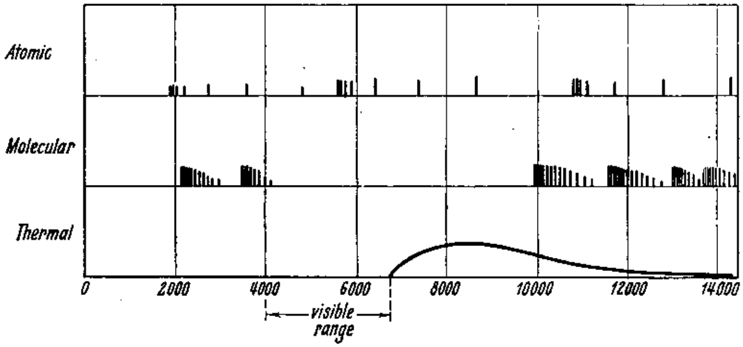


Figure 14. Representation of atomic, molecular, and thermal radiation.

The various wave lengths present in the radiation emitted by a source are determined by dispersing the radiation into a spectrum. This subchapter deals with the instruments and methods used to produce a radiation spectrum both in the visible and the ultraviolet. The next deals with the subject of measuring the intensity associated with the various wave lengths.

The two instruments most frequently used to disperse light into a spectrum are the prism and the grating. When a narrow beam of parallel light falls upon a prism, the different wave lengths present in the beam suffer different deviations in passing through the prism. As a result, each wave length emerges with a slight angular separation from its neighbors. Since, in practice, beams of light are generally divergent rather than parallel, the prism alone gives rise to a spectrum in which there is some overlapping of the wave lengths.

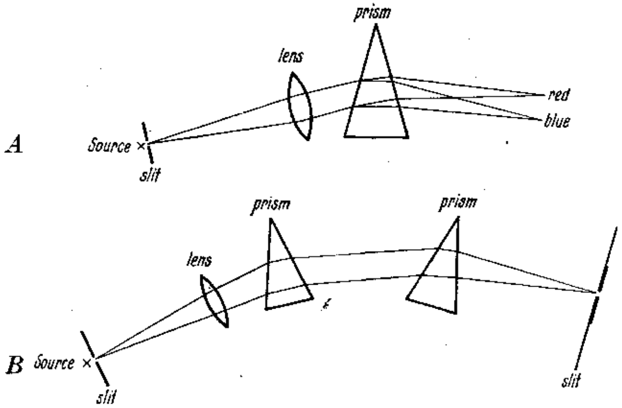


Figure 15. Spectrometers
above: a simple spectrometer; below: a quartz double monochromator.

The simple optical spectrometer (see fig. 15A) prevents this by employing a lens which forms in the eyepiece a narrow image of the slit through which the light enters. By replacing the eye piece by a slit, the instrument may be used as a monochromator or monochromatic illuminator.

For work in the ultraviolet region, the prisms and lens must be of quartz. Fig. 15B represents the optical system of a typical quartz double monochromator. In most instruments the prisms may be rotated by some device which is connected to a drum calibrated in wave lengths. Turning this drum to a certain wave length reading sets the prisms so that only this wave length is permitted to pass through the second slit. Table 4 gives the relative intensities of the lines in the ultraviolet spectrum of the quartz mercury arc as transmitted by such a monochromator.[1]

Table 4. Relative Intensities of Hg Spectral Lines

Wave Length Å	Relative Intensity	Wave Length Å	Relative Intensity
2967	528	2345	20.0
2925	117	2302	10.6
2894	209	2284	13.6
2804	371	2253	6.6
2754	63	2225	7.9
2700	88.6	2191	4.75
2653	735	2150	2.74
2536	1000	1973	0.128
2482	218	1943	0.097
2399	51.5	1850	0.017
2378	40.0		

Gratings are also used to produce spectra of visible and ultraviolet light but since their application is more strictly confined to special work in spectroscopy, a discussion of their characteristics will be omitted.

While monochromators are designed to give high spectral purity of the isolated light, some degree of impurity seems unavoidable. In general, some intensity of radiation of shorter wave length than that desired is transmitted by the instrument. This defect may be greatly reduced by using with the monochromator a filter having a "cut off" on the short wave length side of the desired radiation. By so doing, the intensity of the unwanted wave lengths may be reduced to practically zero. An excellent list of such filters is given in a table (12—5) in *Photoelectric Phenomena* by Hughes and Du Bridge and the ultraviolet portion is reproduced here with their kind permission (see Table 5). The wave lengths given in the table are those at which the filter ceases

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[1] In particular, a Hilger quartz double monochromator.

Table 5. Short Wave Cut-off Filters

Cut-off	Material	Thickness, etc.	Comments
900 A	thin celluloid	30 to 40 mμ	Gradual cut-off
1230 A	clear fluorite	1 to 2 mm	Only very occasional specimens transmit as far as this
1450 A	clear quartz (crystalline)	0.2 mm	Different specimens have practically identical transmission limits
1500 A	clear quartz (crystalline)	2 mm	Air paths have strong absorption below this point
1600 A	clear quartz (crystalline)	20 mm	
1700 A	oxygen in a quartz (crystalline) cell	10 mm, at atmos. pressure	
1750 A	water in a quartz (crystalline) cell	20 mm	Steep cut-off. (Lyman finds, however, that 0.5 mm of water has a sharp cut-off at 1729 A)
1750 A	clear fused quartz	0.3 mm	Transmissions: 1849 A, 24% 1971 A, 36% 2002 A, 40%
1850 A	quartz mercury lamp		1850 A is the shortest wave length emitted by a new lamp
2000 A	clear fused quartz	3 mm	Transmissions: 2000 A, 0% 2100 A, 56% (different specimens vary widely in transmission)
1900 A	acetic acid in water	32 mm, 1 part acid in 1000 parts water	The concentrations are merely rough estimates; it is best to find by trial the desired concentration
2000 A	acetic acid in water	32 mm, 1 part acid in 200 parts water	
2200 A	code 970[1]	5 mm	Gradual cut-off; "solarizes" with short wave lengths
2200 A	calcite	10 mm	
2300 A	rock salt	12 mm	Lyman and Pfluger, however, found rock salt to transmit as far as 1750 A

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[1] standard filters of the Corning Glass Works.

Cut-off	Material	Thickness, etc.	Comments
2350 A	p-dichlorbenzene	50 mm; sat. solut. in water	
2450 A	tartaric acid	3.2 mm; 1 part sat. solut. in 64 parts water	
2500 A	thiophene	50 mm; sat. solut. in water	Steep cut-off
2800 A	benzol		Steep cut-off
2800 A	code 971[1])	2.1 mm	Fairly steep cut-off
2900 A	code 971[1])	4.9 mm	Fairly steep cut-off
3000 A	pyrex[1])	1.0 mm	

to transmit appreciably. These authors point out that "a filter is seldom found in which the transmission changes from 50 per cent to 1 percent or less in 200 Å".

In some cases it is possible to find a source giving widely separated lines in a desired wave length region. By using a suitable filter with such a source, it frequently occurs that but one line is transmitted. Such a combination may give much greater intensity than could be obtained by the use of the monochromator.

Because of the great intensity of solar radiation and the possible effects of daylight on biological reactions, some data are given on the short wave length limit of the solar spectrum. This limit of the solar spectrum as recorded by a photographic plate at various altitudes of from 50 to 4560 meters was found by one observer to be 2910 Å. Another experiment carried out at 9000 meters showed energy present at 2897 Å. The conclusion is given that the intensity, at the surface of the earth, of the solar radiation of wave length 2900 Å is not more than one-millionth of the intensity at 3150 Å. This sharp cut-off is ascribed to the ozone present in the upper layers of the atmosphere. Nevertheless, though the absorption approaches asymptotically 100%, we must keep in mind the possibility that extremely small intensities of the lower wavelengths exist in day light. This is important since in biological radiations, we are dealing with very low intensities, far beyond detection by photographic plates.

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[1]) standard filters of the Corning Glass Works.

Table 6 gives the absorption of ultraviolet by 16.97 mm of distilled water. This, together with the absorption spectrum of oxygen, shows plainly why in biological radiations, no experiments are carried below 1900 Å.

Table 6. The Absorption of Ultraviolet in Distilled Water (16.97 mm)

Wave Length Å	Absorption %
1860	68.9
1930	24.5
2000	14.2
2100	9.8
2200	9.2
2300	5.6
2400	5.2
2600	4.2
3000	2.5

F. THE INTENSITY MEASUREMENT OF VISIBLE AND ULTRAVIOLET RADIATION

Arranged in order of increasing sensitivity, the detectors of visible and ultraviolet light are: the thermocouple, the photographic plate, the photoelectric cell and the photoelectric counter.

(1) **Thermocouple**: The thermocouple consists of a circuit composed of two dissimilar metals or alloys (see fig. 16a).

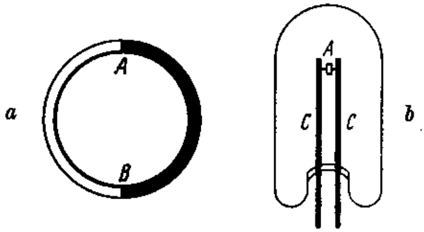

Figure 16. Thermocouples left: a two-metal thermoelement; right: a modern high-sensitivity thermocouple.

If the junctions are maintained at different temperatures, a current will flow in the circuit, which is proportional to the temperature difference of the two junctions. Modern high-sensitivity thermopiles are frequently built as diagrammed in fig. 16b in which A is a very light bit of thin gold leaf, 1 or 2 mm^2 in area. The gold leaf is supported by two fine wires, one of a bismuth-antimony alloy, the other of bismuth-tin, which are soldered to the heavy leads, C. By using pieces of small dimensions, the heat capacity of the instrument is low, as is the heat loss by conduction; thus, the sensitivity is high. Used with a sensitive galvanometer, such a thermopile will give a detectable deflection when the radiation falling upon the gold leaf has an intensity of approximately 3×10^{-10} cal/cm²/sec. or 1×10^{-2} ergs/cm²/sec. The advantage possessed by the thermopile over the other means of intensity measurement is that its response is quite independent of the wave length of the radiation. For this reason, it is often used to calibrate a source of ultraviolet for instance in [illegible]

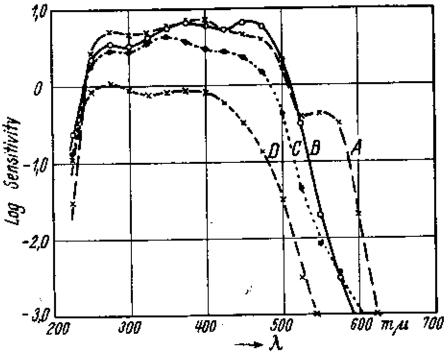

Figure 17. Spectral sensitivity curves of Eastman plates
A: Eastman Speedway; B: Eastman 40; C: Eastman 35; D: Eastman Process.

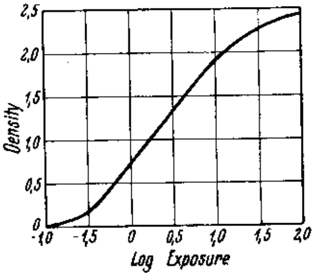

Figure 18. Characteristic curve of a photographic plate.

wave

length limit of the work function depends upon the treatment given the surface. It is rare in this work to find the results of two investigators coming within more than approximate agreement.

the window covered so that no light can enter the cell, the galvanometer reads zero indicating that no current is flowing in the circuit. If light is allowed to fall upon the metal surface, photoelectrons are ejected from the atoms of the metal film and are attracted to the central wire. These electrons flowing through the wire cause the galvanometer to deflect, which is a measure of the photoelectric current.

Necessarily, in such cells, the energy, $h\nu$, of each quantum to be measured must be greater than the energy required to remove an electron from the surface, that is $h\nu > E\infty - E_0$. This equation applies to isolated atoms. In a photoelectric cell, the photoelectrons must not only be removed from the atoms but must be shot away from the metal surface and eventually even through it. This requires a little more energy. The energy required to remove a photoelectron from a photoelectric surface is called the "work function", W_0.

The situation in the sensitive surface of a photoelectric cell is further complicated because of the impossibility of having this surface consist of one kind of atom. With the best high vacuum technique known today it is impossible to prevent contamination with various atoms, chiefly those of the gases prevalent in the air, such as oxygen, hydrogen and nitrogen. The result is that W_0 for a given metal depends considerably upon its history and the care with which it has been freed from gases. The purest surfaces are prepared by distilling metals in a high vacuum. Table 7 gives the photoelectric work functions, W_0, for various metals as obtained by different investigators; only a few metals being given, since these may be regarded as representative. (Further data may be found in *Photoelectric Phenomena*, HUGHES and DU BRIDGE). The threshold wave length in Å refers to the longest wave length which will eject photoelectrons from a given surface, and this may be transformed into a value in electron volts—then called the photoelectric work function — by the equation

$$W = \frac{12336}{\lambda \text{ in Å}}.$$

The first three columns show how the value of the long wave length limit or the work function depends upon the treatment given the surface. It is rare in this work to find the results of two investigators coming within more than approximate agreement.

Table 7. Photoelectric Work Functions of the Metals

Metal	Threshold Wave Length in Å			W_0 in volts
	no outgassing	partial outgassing	extended outgassing	
Ag	3213	2888	2610 (20°C)	4.73
	3250	3150	2700 (600°C)	
	3364			
	3390			
Al	3460	3652		
	3595			(2.5 to 3.6)
	3650			
	4132			
	4770			
	5000			
Cd	3050			(4.00)
	3130			
	3140			
	3302			
K	>4360	5500	5500	(1.76 to 2.25)
	6700	5800		
		5800		
		6200		
		6500		
		7000		
		7000		
Li	5260	4300	5400	(2.1 to 2.9)
		5200		
		5600		
		5800		
Mg	3300	>3650		(<3.40)
	3820			
	7000			
Na	5830	5500	5000	1.90 to 2.46
	6100	5500		
		6400		
Ni	3050	2700	2463	5.01
	3365	3040		
Zn	3016	3182	3720	3.32
	3200		3460	3.57
	3425		(Single	
	3760		crystal)	
	4009			

The fourth column gives the best estimate of the value of W_0 that could be made for the various metals.

(4) The Photoelectric Counter. The photoelectric tube counter is merely a photoelectric cell of a special geometrical shape. In such an instrument, the individual photoelectrons are recorded, making it much more sensitive than the photo cell in which photoelectron currents are measured. The lowest intensity which is measurable with a counter is about 10^{-9} ergs/cm^2/sec. or about 500 quanta/cm^2/sec.

In a counter, the photoelectrically active element is deposited on the inside walls of a cylinder, and the collector is a fine wire insulated from the cylinder and stretched along its axis (see fig. 20). It is filled with some gas to a pressure of about 10 cm. of mercury. The metal tube is connected to the negative terminal of a battery of perhaps 1000 or 1500 volts, and the collecting wire to an amplifier, such as is found in a radio receiver. Slits may be cut in the cylinder to let in the light, or it may be allowed to shine in the ends of the cylinder. Each time a photoelectron is ejected from the walls of the tube, it will be accelerated toward the wire (which is positive by 1000 or 1500 volts) and in its course through the gas will ionize some of the atoms with which it collides. The electrons thus freed are also attracted toward the wire and in turn form more ions. In a very small fraction of a second all these negative ions will reach the wire. This momentary movement of charge is equivalent to a small current which when amplified, produces a "plunk" in the loud speaker. The number of "plunks" per second indicates the number of photoelectrons ejected per second; this number is proportional to the number of quanta striking the inner wall of the tube each second. While in use, the counter gives a few counts per minute when no radiation from the source under experiment is falling upon it. These are due to cosmic radiation, local gamma radiation and α, β and γ rays from radiocative impurities in the metal of the wire and tube; they are

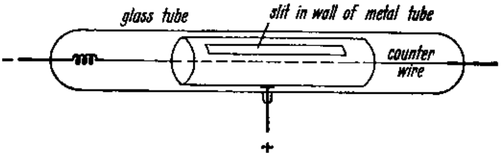

Figure 20. Photoelectric tube counter.

called "dark counts", "strays" or background radiation. The difference between the number of counts when the counter is exposed to and shielded from radiation is proportional to the intensity of the incident radiation. Fig. 21 illustrates data taken with an aluminum counter by Frank and Rodionow (1931) to prove the radiation from chemical reactions and from tetanized muscle. The dotted line indicates the number of "strays" and the solid line the total number of counts when the counter is exposed to the radiation, a 5 minute exposure being alternated with 5 minutes of shielding.

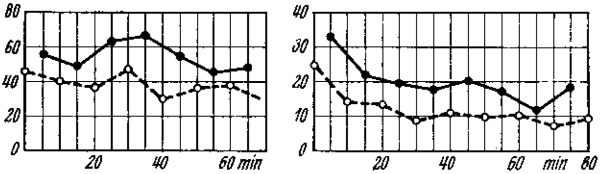

Figure 21. The ordinates are the number of impacts obtained per 5 minute interval, when the counter is exposed alternately for 5 minutes and shielded from the source of radiation. The source of radiation was at the left the chemical reaction $K_2Cr_2O_7 + FeSO_4$, at the right a tetanized sartorius muscle of the frog.

It has been found that for the ordinary counter (as well as for the photoelectric cell) only about 1 quantum in 10000 striking the walls ejects a photoelectron into the gas of the tube. The number of quanta incident upon a surface divided by the number of photoelectrons ejected, or the average number of quanta required to eject one photoelectron, is called the *photoelectric yield* of the surface. The photoelectric yield is the reciprocal of the efficiency of a surface. A perfectly efficient surface would yield one photoelectron for every incident quantum.

Yields of surfaces in photoelectric counters have never been as high as those in photoelectric cells because the active gases H, O, etc. with which these counters are filled will reduce the sensitivity of the surface. It should be possible to fill a counter having a highly sensitive surface with some inert gas which will not reduce the sensitivity. Werner (1935) recommends $75\,{}^0/_0$ Ne and $25\,{}^0/_0$ He. Howewer, the experience of one of the authors shows that it is difficult to obtain sharply defined counts with this mixture. More literature is quoted in Chapter IV, p. 91.

The values of Table 8 represent maximum yields obtained by experienced workers. Generally, yields of 100 or even 1000 times these values are considered to be good.

Table 8. Highest yields obtained with various surfaces at the maxima of their spectral distribution curve

Metal	Wave length in Å	Yield expressed in coulombs per cal.	Yield expressed in quanta per electron
Al	2360	0.01×10^{-2}	763
K	4200	3.00×10^{-2}	28
Mg	2500	5.20×10^{-2}	16
Na	3400	0.57×10^{-2}	134
