The Average Energy Required to Produce an Ion Pair in Xenon with 0.16A X-Rays

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The average energy, ϵ, which is required to produce an ion pair in xenon by use of x-rays of wave-length between 0.12A and 0.26A as a source of energy, was determined. Two measurements of the power were made; one with a lead disk thermopile which absorbed 97 percent of the incident radiation and the other with a thin silver disk thermopile which absorbed 8.9 percent. The ionization measurements were made with a glass ionization chamber which was filled with xenon at a pressure of 2.22 atmospheres. This chamber absorbed 15.9 percent of the incident radiation. The value of ϵ was found to be 21.3 ± 0.8 electron-volts.

INTRODUCTION

THE purpose of this investigation was to determine the average energy, ϵ, which is required to produce an ion pair in xenon by moderately hard x-rays.

Since ϵ is a slowly varying function of the wave-length[1] in this region, the value which was determined in this experiment may be useful over a wide range in the hard x-ray region for xenon-filled ionization chambers.

The work of many experimenters[2] using slow electrons as sources of energy shows that ϵ is markedly higher for electrons of low velocity. Gerbes's[1] correction of Eisl's[3] values shows that ϵ for air is about 4 percent higher for incident electrons of 10-kev energy than for electrons of 60 kev, although nearly all of the increase occurs below 20 kev.

The comparison of values of ϵ, which are determined with electrons as the ionizing agency, with those in which x-rays are used, is simple only if the gas is pure and if the energy which is required to remove an electron from an atom is small compared to the energy of an incident electron or quantum. For example, Gaertner,[4] using x-rays of wave-length 1.54A, has determined the absolute value of ϵ for argon to be 28.4 electron volts. The primary processes are the production of photoelectrons having energies of 4.8 kev and of some Auger electrons having energies of 3.2 kev. An extrapolation of Gerbes'[5] electron values for argon gives 28.4 electron volts at about 4.5 kev.

In experiments with gas mixtures such as air, there is an additional complication that argon, which constitutes 1 percent of the gas, absorbs 10 percent of the x-rays of wave-length 1.54A. The ion pairs are produced by electrons having energies of 8 kev, 4.8 kev and 3.2 kev. For these reasons even the relative values of ϵ, which are determined by β-ray sources, will not agree with those which were determined by x-ray sources except in special cases.

GENERAL PLAN OF EXPERIMENT

The problem of determining ϵ splits into two parts; that of determining the power in an x-ray beam by a measurement of the heat evolved and that of determining by an ionization current measurement the number of ion pairs produced by the same or a related x-ray beam.

The total x-ray power, P_0, of a beam passing through an aperture 0.500 cm in diameter was measured by allowing the x-rays to be absorbed in a thick lead disk. The power was calculated both from the rate of increase of temperature and from the ultimate temperature. Because the disk was thick and because the K radiation was not excited the losses other than conversion to heat in this case were small. This was checked by a second thick lead disk thermopile of different design.

The ideal method would have been to absorb completely this same x-ray beam in a xenon-filled chamber and measure the saturation cur-

[1] W. Gerbes, Ann. d. Physik **23**, 648 (1935).
[2] Among others: J. Thomson, Proc. Roy. Soc. of Edin. **51**, 127 (1930–31); H. Pigge, Ann. d. Physik **20**, 233 (1934); L. Freund, Ann. d. Physik **22**, 748 (1935); G. A. Anslow and M. Watson, Phys. Rev. **50**, 162 (1936); E. Breunig, Ann. d. Physik **25**, 467 (1936).
[3] A. Eisl, Ann. d. Physik **3**, 277 (1929).
[4] O. Gaertner, Ann. d. Physik **21**, 564 (1934–35).
[5] W. Gerbes, Ann. d. Physik **30**, 169 (1937).

rent. This seemed impractical. A much smaller chamber which absorbed approximately one-fifth of the primary radiation was used. A smaller aperture 0.0676 cm in diameter was necessary in order to obtain a saturation current without producing ionization by collision. The absorption from the x-ray beam was calculated and then the saturation current, i_0, which would have been produced by the ideal method was computed. The average energy, ϵ, in electron volts, which is required to produce an ion pair, is $\epsilon = P_0 e / i_0$ where P_0 = power in electron volts per sec., i_0 = saturation current, and e = charge of an electron.

A second determination of ϵ was made in which the power was calculated from the ultimate temperature of a thin silver disk. The undetermined losses of the silver and the xenon were comparable and a systematic error of these losses had little effect on the ratio which was used to find ϵ. This is true because the atomic numbers of silver and xenon are nearly the same and because each absorbed only a small fraction of the x-rays. However the experimental error in this method was higher.

Power Measurements

The x-rays were produced in a G.E. model XPT tube. The tube was operated on half-wave rectified voltage of 100 peak kv and the current in the tube was 25 ma. The tube was mounted in a lead box which was filled with oil. The x-rays were filtered consecutively by the tube wall, 2 cm of oil, 1 mm of Cu and 1 mm of Al.

Microphotometric measurements of a film, which was exposed to the diffracted beam from a calcite crystal, were used to obtain the curve shown in Fig. 1. A correction was made for the different absorption of the various wave-lengths by the film. No correction was made for either the percent reflected from the crystal for different wave-lengths or for the effect of the fluorescent screens.

For the power measurements the beam was limited by the focal spot whose projection on a plane perpendicular to the beam was 1 cm by 0.3 cm. The beam was also limited by a circular aperture 20 cm from the focal spot. The aperture for all power measurement was 0.500 cm in diameter. An additional circular aperture 0.9 cm

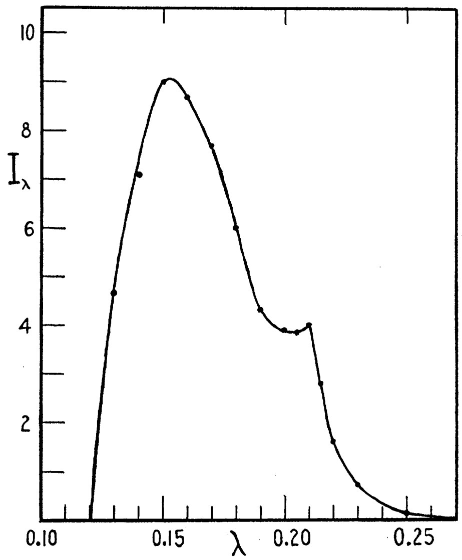

Fig. 1. Intensity in arbitrary units as a function of wave-lengths in angstroms.

in diameter was placed 14 cm from the target to limit scattered radiation. A lead shutter was used to shut off the x-ray beam without electrical disturbance.

A holder was rigidly attached to the slit system so that the thermopiles and ionization chamber could be removed and accurately replaced.

Three thermopiles were used. The absorption blocks of thermopile A were made of two circular lead disks superimposed so that the x-rays were absorbed by 0.0954 cm of lead which was the sum of the thicknesses. The disks were electrically insulated from each other by a little pyroxylin so that the thermocouples could be placed in series. The thermal capacity of each disk was calculated to be 0.00560 cal./C.

The absorption blocks of thermopile B were made of two semicircular electrically-insulated lead disks which were fitted together to form a circle. The x-rays were absorbed by the thickness of either disk which was 0.0886 cm. The thermal capacity of each disk was 0.00520 cal./C.

The absorption block of thermopile C was made of a single circular silver disk with a thickness of 0.00250 cm and a thermal capacity of 0.000463 cal./C.

In each case the thermocouple wires were No. 40 Nichrome and constantan which were cut from a piece which had been calibrated. The

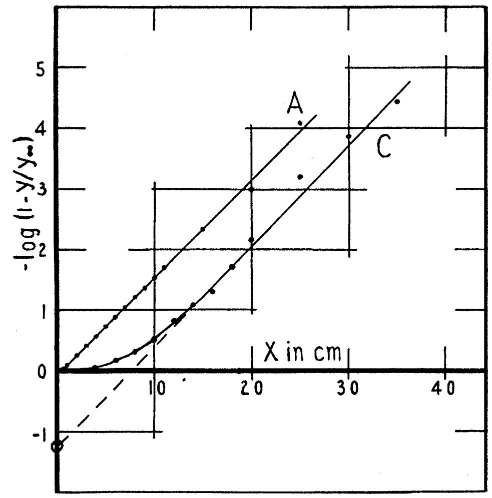

FIG. 2. Galvanometer deflections, y, as a function of the distance on a circumference of the drum. $x/t=0.272$ cm/sec. in the curve for thermopile A. $x/t=3.35$ cm/sec. for thermopile C.

amounts of solder and pyroxylin which were used were of correction magnitude. The disks were suspended in air by the thermocouple wires from the cold junctions which were copper blocks. The thermopiles including the cold junctions were surrounded by brass cases. The windows of the thermopiles were the same as that of the ionization chamber, i.e., 0.096 cm of glass and 0.005 cm of Al.

For a measurement of the power a thermopile was placed in series with a galvanometer and a record of the galvanometer deflections as a function of time was obtained by allowing the galvanometer spot to strike on a film which was on a uniformly-rotating drum.

From the application of the conservation of energy to the disks the electromotive force, E, developed by the thermopile is

$$E=\frac{\sigma P}{\omega C}(1-e^{-\omega t})$$

where σ = the e.m.f. due to unit temperature difference, P = power absorbed in the disks, ω = an experimentally determined constant (depending on the thermal capacity of the disk and the constants of heat transfer from the disk), and C = the thermal capacity of one disk. Then the usual galvanometer equation becomes

$$\frac{d^2y}{dt^2}+2\beta\frac{dy}{dt}+\gamma^2 y=\frac{\gamma^2 b\sigma P}{\omega C}(1-e^{-\omega t}).$$

Since in this experiment $\omega>\beta$, the solution of the equation becomes after a time

$$y=\frac{b\sigma P}{\omega C}(1-Ae^{-\omega t}), \quad (1)$$

where

$$A=\frac{\gamma^2}{\omega^2-2\beta\omega+\gamma^2}.$$

At

$$t=\infty,$$

$$y_\infty=b\sigma P/\omega C \quad (2)$$

and

$$P=\omega C y_\infty/b\sigma. \quad (3)$$

From Eqs. (1) and (2)

$$-\log(1-y/y_\infty)=\omega t-\log A. \quad (4)$$

As shown in Fig. 2, ω was determined from the slope of the graph of Eq. (4) with experimental values of y/y_∞ and t. A check on the value of ω was made from the values of β, γ and A. The values of β and γ of the galvanometer were determined from the calibration trace. From Eqs. (1)

$$P=\frac{Ce^{\omega t}}{b\sigma A}\frac{dy}{dt}. \quad (5)$$

Equations (3) and (5) were used to determine the power absorbed.

From a calibration of the thermocouple wires σ equals 39.4×10^{-6} volt/°C.

Table I shows values of the power absorbed in the disks of thermopile A. These values were calculated from individual values of b, ω, t, etc. The following are average values of these data; $b=4.93\times10^6$ cm/volt; $\omega=0.0440$ sec.$^{-1}$; $A=1.09$; $y_\infty=2.68$ cm. The time rates of deflection of the galvanometer were of the order of 0.1 cm/sec.

TABLE I. *The power absorbed in the disks of thermopile A.*

Film Number	Time in Sec.	Thermal Condition of Thermopile	Calculated Value of Power in Cal./Sec.
1	∞	equilibrium	3.37×10^{-6}
1	7.35	heating	3.46
1	11.03	heating	3.44
1	7.35	cooling	3.46
1	11.03	cooling	3.46
2	∞	equilibrium	3.35
2	7.35	heating	3.41
2	11.03	heating	3.52
2	7.35	cooling	3.42
2	11.03	cooling	3.53
	Average $(3.44\pm0.01)\ 10^{-6}$ cal./sec.		

The power absorbed by the thick lead disks of thermopile A was 144.0 ± 0.5 ergs/sec.

In case of measurements with thermopile C, the galvanometer deflections were so small that the films were magnified 12.4 times. The trace was then about 2 mm wide with a fairly definite edge. The following data were taken from an average of ten films. $b=6.41\times10^7$ cm/volt; $\omega=0.55$ sec.$^{-1}$; $\beta=0.85$ sec.$^{-1}$; $\gamma=0.95$ sec.$^{-1}$; $A=3.45$. By Eq. (2) the power absorbed in the thin silver disk of thermopile C was 9.9 ± 0.3 ergs/sec.

To calculate the incident power, P_0, from the absorbed power, P, when the photoelectrons are not all absorbed,[6] A. H. Compton's[7] equation becomes

$$P=(FR-Q)P_0$$

where F is the fraction of the x-rays which is removed from the main beam and is equal to $1-e^{-\mu l}$. R is the fraction of the power, FP_0, absorbed in the thermopile or chamber if no electrons escape from it.

$$R=1-w_K\frac{\tau}{\mu}\frac{r-1}{r}\frac{\lambda}{\lambda K_\alpha}e^{-\tau_K d}-\frac{\sigma}{\mu}e^{-\tau d}. \qquad (6)$$

Here Q is the fraction of the power, P_0, which escapes as kinetic energy of electrons.

$$Q=0.140\tau S(1+e^{-\mu l})\times\left[\frac{r-1}{r}\left(1-\frac{\lambda}{\lambda_K}\right)^3+\frac{1}{r}\left(1-\frac{\lambda}{\lambda_L}\right)^3+\frac{1.20(1-w_K)(r-1)}{r}\left(\frac{\lambda}{\lambda K_\alpha}-\frac{\lambda}{\lambda_L}\right)^3\right], \qquad (7)$$

where w_K is the K fluorescent yield, r is the K absorption jump ratio, S is the range of photoelectrons having an energy $h\nu$ corresponding to the incident wave-length, λ.

The losses for thermopile A are negligible so that $R=1$, and $Q=0$. The $I_\lambda=f(\lambda)$ curve of Fig. 1 was used for a mechanical integration to find the fraction of the x-rays absorbed.

$$F=\frac{\int I_\lambda(1-e^{-\mu l})d\lambda}{\int I_\lambda d\lambda}=0.971.$$

Table II. *Average of galvanometer deflections.*

Diameter of Aperture in cm	Galvanometer Deflection in cm	Shadow Effect	Corrected Current in amp./cm² of Opening
0.0526	3.99	4.7%	3.96×10^{-7}
0.0676	7.06	3.0%	4.16×10^{-7}
Average $(4.06\pm0.10)\,10^{-7}$ amp./cm²			

Then

$$P_0=\frac{P}{0.971}=148.3\pm0.5 \text{ ergs/sec.}$$

for cross section area of 0.1963 cm².

The value of P_0 which was obtained from thermopile B agreed with that of thermopile A within 0.5 percent.

For thermopile C, the fraction, F, was computed to be 0.089. The method used was the same as for thermopile A.

Since accurate values of μ of Ag and Xe are required, a study of the data of Allen,[8] Hahn,[9] White[10] and Müller[11] was made by the method used by Hahn.[9] The equation $\tau_a/Z=1.224\times10^{-5}Z^{2.63}\lambda^{2.55}$ seemed best to represent the data from 0.13A to 0.31A and from $Z=46$ to $Z=58$.

In calculating R for the thin silver disk of thermopile C, the average of $e^{-\tau d}$ could not be calculated from the average d. The fraction escaping from one side of the disk from a depth b is

$$b\tau\int_{b\tau}^{\infty}u^{-2}e^{-u}du,$$

in which $u=b\tau$ sec. θ. This integral was evaluated for several layers and the average showed that 0.66 of the K radiation and 0.87 of the scattering radiation were escaping. With these values for $e^{-\tau d}$ and $e^{-\tau_K d}$ in Eq. (6), $R=0.84$. In this case Q was calculated to be 0.0059. Hence

$$P=(0.089\cdot0.84-0.0059)P_0$$

or

$$P_0=144\pm4 \text{ ergs/sec.}$$

for a cross section area of 0.1963 cm².

Ionization Measurements

The x-ray tube was operated under the same conditions as those for the power measurements,

[6] N. L. Walbridge, Rev. Sci. Inst. **12**, 546 (1941).
[7] A. H. Compton, Phil. Mag. **8**, 961 (1929).
[8] S. J. M. Allen, *X-rays in Theory and Experiment*, by Compton and Allison (D. Van Nostrand Co., 1935).
[9] T. M. Hahn, Phys. Rev. **46**, 149 (1934).
[10] T. N. White, Phys. Rev. **46**, 865 (1934).
[11] I. Müller, Ann. d. Physik **32**, 625 (1938).

but in order to obtain saturation currents without ionization by collision, smaller apertures were necessary. Two apertures were used whose diameters were 0.0526 cm and 0.0676 cm. These apertures were made in lead plates 3 mm thick by drilling 1.5 mm with a 1-mm drill and then drilling the opening with a needle through the remaining 1.5 mm of lead. The center of the focal spot of the tube was on the axis of the aperture in each case. This was shown by rotating the apertures about their axes and obtaining the same ionization currents.

Although these openings were small, the shadow effect which was due to the length of the cylindrical opening, was of correction magnitude.

The ionization current was measured before and after the power measurements to insure that conditions had remained the same. The ionization currents were measured by a galvanometer whose sensitivity was 2.06×10^{-10} amp./cm at the distance of four meters.

The cylindrical ionization chamber was made of Pyrex glass with tungsten seals. One of the tungsten wires formed one electrode, the other electrode was of Al and formed almost a complete lining for the glass chamber. The front window of the chamber was 0.096 cm of glass and 0.005 cm of Al. The inside volume of the chamber was 62.7 cc and it was filled with 0.815 g of Xe, at a density of 0.0130 g/cc. The inside length of the chamber was 2.69 cm and its radius was 2.1 cm.

The galvanometer deflections in Table II were averaged from several sets of data.

The area of the aperture which was used in the power measurement to find P_0, was 0.1963 cm^2. Hence

$$i=(0.80\pm 0.02)\times 10^{-7} \text{ ampere}$$

where i is the saturation current which would have been produced in this chamber by the beam which was used for the power measurements.

The factor F for the xenon-filled chamber was found in the same way as it was found for the silver disk.

$$F=0.159$$

The factor R was easier to compute since d was small and the average of $\exp[-\tau d]=\exp[-\tau\bar{d}]$. For this ionization chamber $\bar{d}$ was calculated to be 2.05 cm. The average distance, $\bar{d}$, was found from the average of several layers. So that $R=0.76$. In this case $Q=0.0056$.

From

$$i=(FR-Q)i_0,$$
$$i=8.57i_0,$$

then

$$i_0=6.85\times 10^{-7} \text{ amp.}$$

Where i_0 equals the saturation ionization current which would have been produced if the x-ray beam which was used in the power measurement had been completely absorbed in xenon and if none of the power had escaped as radiation or kinetic energy of electrons.

Results

From the power measurement with the lead disk thermopile $\epsilon=21.6\pm 0.8$ electron volts, and from the power measurement with the silver disk thermopile $\epsilon=21.0\pm 0.8$ electron volts. The two values are considered to be equally reliable. Although the power measurement with the lead disks is more accurate than that with the silver disk, the value of ϵ obtained from the former is more dependent on the accuracy of the $I_\lambda=f(\lambda)$ curve, and is dependent on the absolute value of μ of Xe and the absolute values of the power losses while the value of ϵ obtained from the latter is less dependent on the $I_\lambda=f(\lambda)$ curve and is dependent on the relative value of μ of silver and xenon and on the relative values of the power losses. For these reasons an average value is taken and $\epsilon=21.3\pm 0.8$ electron volts when the source of the energy is x-rays of wave-length 0.16A. Other values of ϵ in xenon are 22.1 electron volts for x-rays of wave-length 1.54A, which was determined by Gaertner[12] and 20.7 electron volts for alpha-rays which was determined by Gurney.[13] These values are not directly comparable since ϵ is a slowly varying function of the energy of the incident electrons.[1]

In this experiment the photoelectrons from the K level had energies of about 42 kev, and the value which was determined here should be comparable to β-ray values for which the source is electrons of approximately that energy.

In conclusion, the author wishes to express his thanks to Professor R. J. Stephenson for suggesting this problem and to Professors A. H. Compton, S. K. Allison and R. J. Stephenson for their advice and encouragement.

[12] O. Gaertner, Ann. d. Physik **23**, 255 (1935).

[13] R. W. Gurney, Proc. Roy. Soc. London **107**, 322 (1925).