Waller theory as applied the relative intensities of modified and unmodified scattering it cannot be claimed that the experimental evidence is as yet either complete or satisfactorily concurrent.

Wave-Length of the Modified Band

Previously published measurements[15] of the magnitude of the Compton shift showed that the wave-length of maximum intensity is separated from the unmodified line by a wave-length interval slightly less than that given by the Compton formula,[31] the difference being found proportional to the square of the wave-length of the incident radiation. This shift defect was ascribed to the binding energy of atomic electrons[32] and Bloch[5] found it possible, upon certain approximately fulfilled assumptions, to calculate its magnitude. The defect has also been theoretically justified by Burkhardt.[8]

The quantitative agreement between theory and the observations, however, is now somewhat less satisfactory than it appeared to be in 1934, for the following reasons: (1) Errors in calculation have been discovered which when corrected increase the theoretical defects by some 10 percent. (2) The choice of numerical values of binding energies for use in the theoretical calculations has been questioned. Any alteration of the values used must be in such a sense as to increase further the theoretical defects. (3) Burkhardt has called attention to a neglected source of shift defect associated with the sign of the electron momentum, which requires a further increase in the theoretical value of the defect.

It is not certain that this widening gap between predicted and observed shift defects can be explained by the fact that the scatterers have actually been solids whereas theories have been concerned with free atoms. Precise shift measurements using monatomic gaseous scatterers are expected to clarify this point.

[31] In a summary of evidence on the question of the correctness of the original Compton shift formula Compton and Allison (*X-Rays in Theory and Experiment*, p. 210) assigned chief weight to the results obtained by Gingrich (see reference 20). It is suggested here that consideration discussed above (p. 933) weaken the force of this evidence.

[32] P. A. Ross and P. Kirkpatrick, Phys. Rev. **45**, 223 (1934).

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Columnar Ionization

W. R. Kanne and J. A. Bearden, *The Johns Hopkins University, Baltimore, Maryland*

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The ionization collected from single alpha-particles has been measured as a function of the angle between the path of the particle and the direction of the electric field. Data obtained for electric field strengths of 8, 100 and 500 volts per cm and for air pressures of one and two atmospheres are given. These results have been compared with curves based on the theory given by Jaffé. The agreement between theory and experiment is satisfactory and shows clearly that for low field strengths the loss of ions by recombination is appreciable even for large angles between particle path and electric field. In contrast with values of the recombination coefficient given by Jaffé, it is indicated in the present work that previously accepted values for this quantity are correct. A description of the FP-54 Pliotron circuit which has been used for this work is given.

The theory for the fraction of ions collected from a strongly ionized column of gas by an electric field has been developed by Jaffé.[1, 2] In this theory it is assumed that the electric field separates the intensely ionized column into two parts, one of positive ions and the other of negative ions. During separation these columns broaden by diffusion, and, wherever they overlap, there is a loss of ions by recombination to the extent given by the recombination coefficient.

The expressions given by Jaffé for the ratio of the ions collected to those formed are as follows:

[1] Jaffé, Ann. d. Physik **42**, 303 (1913).

[2] Jaffé, Physik. Zeits. **30**, 849 (1929).

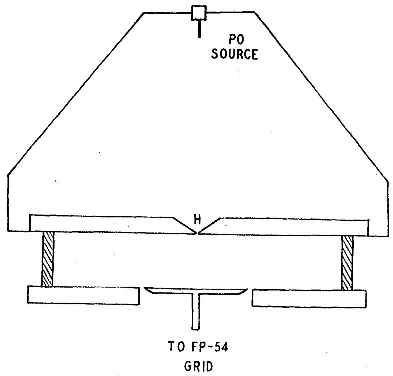


FIG. 1. Ionization chamber used to measure the number of ions collected from alpha-particles making angles from 0° to 45° with the electric field. The separation of the plates is 1 cm.

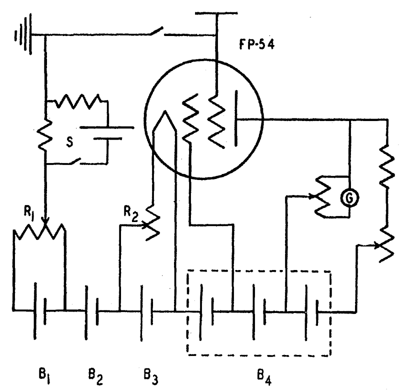


FIG. 2. FP-54 circuit. B_1 and B_2 are 1.5-volt dry cells, B_3 is a 2.5-volt Eveready Air Cell and B_4 is a 6-volt radio storage battery. R_1 is a 4000Ω potentiometer, R_2 is a variable resistance of 10Ω to 12Ω, and R_3 is a variable resistance of 250,000Ω. S serves to check the sensitivity of the tube.

(1) When the path of the particle and the electric field are parallel,

$$i/i_\infty = (pe^{-p}/z)(li\ e^{p+\ln(1+z)} - li\ e^p), \qquad (1)$$

where $z = 2dD/ub^2x$ and $p = 8\pi D/\alpha N_0$.

(2) When the path of the particle is at an angle φ with the electric field, provided that φ is not too small,

$$i/i_\infty = 1/(1+(1/p)(\pi/z')^{\frac{1}{2}}S(z')), \qquad (2)$$

where $z' = u^2b^2x^2 \sin^2\varphi/2D^2$, u is the average mobility[3] of the positive and negative ions, D is the diffusion coefficient, α is the recombination coefficient, N_0 is the number of ion pairs per cm length of path, d is the length of the path, x is the field strength, $b = r_0(4/\pi)^{\frac{1}{2}}$, and r_0 is the mean distance of the ions from the center of the column at the time of formation. For air at one atmosphere Jaffé found $b^2 = 3.2\times10^{-6}$ cm² by fitting the theoretical curves of Eqs. (1) and (2) to experimental data. The integral logarithm of p is $li\ e^p$.

$$S(z') = \frac{1}{(\pi)^{\frac{1}{2}}}\int_0^\infty \frac{e^{-s}ds}{(s(1+s/z'))^{\frac{1}{2}}}.$$

$S(z')$ may be evaluated from the expression[1]

$$S(z')(\pi/z')^{\frac{1}{2}}e^{z'/2} = (i\pi/2)H_0^{(1)}(iz'/2),$$

where H_0^1 is the Hankel function of zero order, and may be found, together with the integral logarithms, in Jahnke-Emde, *Tables of Functions* (Leipzig, 1933). A curve for the ratio of the ionization collected to that actually formed, as a function of the angle, is obtained by joining the one point for $\varphi = 0$ (Eq. (1)) with the valid portion of the curve given by (Eq. (2)).

The present experiment is concerned with the determination of i/i_∞ as a function of angle φ, field strength x, gas pressure, and with the comparison with theory.

EXPERIMENT

In Fig. 1 is shown the parallel plate ionization chamber with a guard ring to assure a parallel electric field. The polonium alpha-particle source was mounted above the chamber and arranged so that the distance to the conical defining hole H could be varied. The source could be rotated about an axis lying in the lower surface of the upper plate and passing through the apex of H. The spread in φ was determined from the diameter of the hole and its distance from the source of alpha-particles. This amounted to ±30 minutes of arc for the observations at one atmosphere and ±2° for those at two atmospheres. The distance of the source was adjusted so that in both cases the range of the alpha-particles was 6 mm after passing through the hole into the chamber. Thus, under no condition was it possible for the particles to strike the lower plate, nor for any of the ions formed to be collected by the guard ring. The gas in the chamber was dry air.

[3] For air at one atmosphere, $u = 1.65$ cm sec.$^{-1}$ volts^{-1}, $D = 3.7\times10^{-2}$ cm² sec.$^{-1}$, and $\alpha = 1.60\times10^{-6}$ cm³ sec.$^{-1}$. For air at two atmospheres, $u = 0.825$, $D = 1.85\times10^{-2}$, and $\alpha = 1.88\times10^{-6}$.

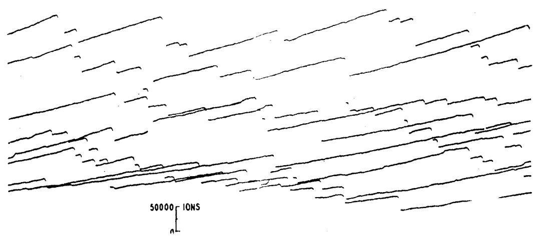


FIG. 3. Sample record.

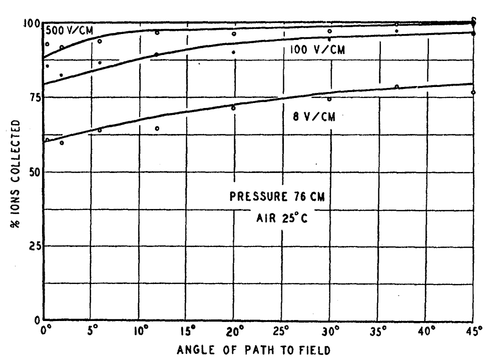
The number of ions collected from single alpha-particles was measured by an FP–54 vacuum tube mounted in an evacuated metal container which eliminated fluctuations of the zero base line due to ions formed near the control grid terminal. The electrical circuit was the simple non-balancing type shown in Fig. 2. An Eveready Air Cell B_3 for the filament supply has been shown to give an exceedingly constant voltage when operated in a circuit of this type,[4] provided its temperature is held constant. A radio storage battery B_4 was used as the plate supply, and dry cells B_1 and B_2 were used across the grid bias potentiometer. With continuous operation it was necessary to recharge the storage battery and replace the dry cells about every four or five months. The air cell lasts about eighteen months.

Observations were made with the control grid "floating." By grounding the circuit through the potentiometer R_1 the potential of the grid could be made the same as that of the grounded guard ring. It is obvious that this was necessary if a parallel field was to be maintained in the ionization chamber.

[4] D. Lyford, Thesis, The Johns Hopkins University (1934).

The changes in plate current were measured with a Leeds & Northrup 2500 R galvanometer (sensitivity 5×10^{-11} amperes per mm) whose deflections were recorded by photographic paper on a rotating drum. When the filament of the tube was operated at the normal 2.5 volts, the sensitivity was about 180,000 mm per volt. A sensitivity of 25,000 mm per volt was found ample for recording the present deflections. Instead of using a galvanometer shunt for reducing the sensitivity, the filament voltage was reduced to 2.0 volts, and the plate resistance increased to 225,000 ohms. The latter method gave the smoother base line. Fig. 3 shows a sample record.

The curves given in Figs. 4 and 5 show the efficiency of ion collection as a function of angle φ. About 100 deflections were measured and averaged for each point on the curves. To determine the saturation current at one atmosphere, the ionization was measured with a field of 1000 volts per cm for an angle of 45°, as is indicated in Fig. 4 by a triangle. At two atmospheres pressure the saturation current could not be reached with the present apparatus, but was determined as follows: For any angle the value of i/i_∞ was calculated from theory and the value of i obtained experimentally. A curve was plotted between i and i/i_∞ for various values of φ and the resulting straight line extrapolated to $i/i_\infty=1$. This, then, gave the saturation value of i. The curve at two atmospheres shows how difficult it is to obtain even partial saturation for air and suggests the use of lower pressures if a large fraction of the ions formed is to be collected. This purpose may also be achieved by choosing a gas for which $D/\alpha N_0$ is large. Such are, for



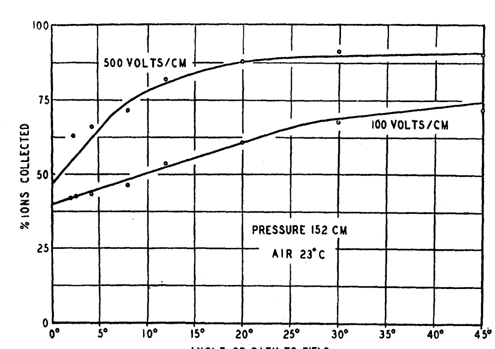


FIG. 4 (left) and Fig. 5 (right). Percent ions collected as a function of the angle between the alpha-particle path and the electric field. The points indicated are experimental and the solid line is an evaluation of Jaffé's theory.

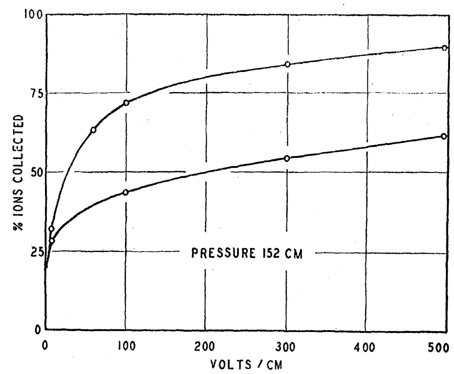


FIG. 6. Saturation curves for air at two atmospheres pressure. The upper curve is for an angle of 45° between the alpha-particle path and the electric field, and the lower curve is for path and field parallel.

example, the noble gases, which have very small electron affinities and thus do not easily form negative ions. For these gases α is then small, for there is very little recombination between free electrons and positive ions.

Computations based on data presented in Figs. 4 and 6 are in satisfying agreement with observations on columnar ionization by Lyford and Bearden.[5] They used a hemispherical ionization chamber of 2 cm radius with an electrode of 0.8 mm radius, the top of which contained a point source of polonium. The ion columns were then always parallel to the electric field. Using nitrogen at one-half atmosphere pressure they reached saturation at about 100 volts. With one atmosphere pressure and a chamber potential of 350 volts they collected 77 percent of the ions, and with two atmospheres they collected 40 percent of the ions. Rough calculations based upon the present results show that, under similar conditions of potential but with air in the chamber, 74 percent of the ions at one atmosphere and 40 percent at two atmospheres should be collected. These comparisons are not exact, since small sections of the ionized column were considered to be in an average field strength, and the fraction of ions which should be collected from these sections taken directly from our curves without considering the length of path d, which enters Eq. (1).

Jaffé[2] has obtained saturation curves for several gases at pressures from one to six atmospheres under conditions approaching parallelism of path and field. Due to the fact that he used a less sensitive electrometer which recorded the integrated effect of large numbers of alpha-particles, his conditions of collimation were not as good as ours—the spread in angle was $\pm 4°$. He found agreement between the experimentally measured ionization and the predictions of Eq. (2) by using his data to calculate recombination coefficients at the various pressures. Eq. (2), however, drops sharply at small angles and deviates considerably at 4° from the curves which combine Eqs. (1) and (2). His values for the recombination coefficient α decrease continually as the pressure is increased from one to six atmospheres instead of reaching a maximum at about two atmospheres.[3, 6] He finds $\alpha = 1.32 \times 10^{-6}$ cm^3 sec.$^{-1}$ for two atmospheres of air. Upon comparing our data at two atmospheres with theory, it is found that the relationship of the four quantities—Eqs. (1) and (2) evaluated for each of the two field strengths—requires that α be considerably greater. Satisfactory agreement is obtained if $\alpha = 1.88 \times 10^{-6}$, as has been given by Langevin.[6]

In conclusion, the columnar effect on the loss of ions by recombination within the parent ion column is appreciable over large angles between the path of the alpha-particle and the electric field, and is correctly predicted by Jaffé's theory under the various conditions of pressure and field strength used in these experiments.

[5] Lyford and Bearden, Phys. Rev. **45**, 743 (1934).

[6] Langevin in Thomson, *Conduction of Electricity through Gases* (Cambridge, 1928), p. 35.