California Institute of Technology

Pasadena, California

THE ABSORPTION COEFFICIENT FOR SLOW ELECTRONS IN GASES

Thesis for Degree

Doctor of Philosophy

Robert B. Brode

1924

THE ABSORPTION COEFFICIENT FOR SLOW ELECTRONS IN GASES.

Robert B. Brode.

Presented to the faculty of the
California Institute of Technology
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy.

May 26, 1924.

THE ABSORPTION COEFFICIENT FOR SLOW ELECTRONS IN GASES

Robert B. Brode.

A beam of electrons is sent thru a space filled with the gas to be measured. An electron is lost from this beam when its interaction with the electric field of an atom is sufficient to change its direction so that it does not enter a collecting chamber placed at the end of the path. This electron is said to be absorbed. If I_o is the number of electrons that start in the beam sent thru the gas and I the number still in the beam after it has passed thru a distance x of gas at a pressure p, then

$$I = I_o e^{-\alpha x p}$$

α is the absorption coefficient of the electrons for unit pressure. It is the total effective absorbing area, in sq. cm, of all of the molecules in a cubic centimeter of gas at a pressure of 1 mm of Hg, if x is given in cm and p in mm of Hg. The effective absorbing area of a molecule may be found by dividing α by the number of molecules in a cubic centimeter at a pressure of 1 mm of Hg, or 3.65×10^{16}. If this absorbing area of the molecule is taken as a circular disc, its radius will be given by, $r = \sqrt{\alpha} \cdot .30 \cdot 10^{-8}$ cm.

This method of measuring the effective size of molecules was first used by P. Lenard[1] in 1903. Lenard used a photo-electric source of electrons and sent them thru a path of about 8 cm length. He measured the initial and final intensity of the electron stream and from his observations computed the value of α for air, carbon di-oxide, hydrogen and argon. His observations were taken for velocities of electrons from 4 to 4000 volts. In the cases of air and hydrogen he took some observations at 30,000 volts.

H. F. Mayer[2] and C. Ramsauer[3], working in Lenard's laboratory in 1921 repeated the experiment with greater accuracy for low speed electrons. Mayer used an equi-potential thermal source of electrons and varied his path length as well as his pressure. By taking two observations at different path lengths, he obtained two equations,

$$I_1 = I_{10}\, e^{-\alpha x_1 p} \quad \text{and} \quad I_2 = I_{20}\, e^{-\alpha x_2 p}$$

Solving these two equations for α gives,

$$\alpha = \frac{1}{(x_1 - x_2)\, p} \cdot \log \left(\frac{I_1}{I_2} \cdot \frac{I_{20}}{I_{10}} \right)$$

In this equation only the ratio of the currents occurs. The total emission of the filament is not I_{10} or I_{20} as some of the electrons go to the grid thru which the beam passes. However I_{10} and I_{20} are proportional to the total current and their ratio will eliminate the factor of proportionality.

Ramsauer used a photo-electric source of electrons. To get a beam of uniform velocity electrons at low speed, he used a series of slits arranged in a circle and bent the electrons in this circle by means of a magnetic field. The radius of the circle in which a uniformly moving electron moves due to a magnetic field is obtained from the equation,

$$H r = 3.3\sqrt{V}$$

H is the magnetic field strength in gauss, V the velocity of the electron in volts, and r the radius in centimeters. By making the slits narrow in comparison with the radius of the circle a beam of quite uniform velocity electrons can be obtained. Mayer and Ramsauer were able to carry their measurements down to velocities of .7 volts. They studied hydrogen, nitrogen, argon, helium and neon. For each of these gases, except argon, they found that the value of α was nearly constant, decreasing only a little as the velocity was increased from .7 to 10 volts. In the case of argon they found that α had a maximum value at about 13 volts. As the velocity was decreased from 13 volts the value of α decreased steadily until at .7 volts it was 1/30 th of its maximum value. With increasing velocity above 13 volts the value of α decreased steadily. It appears from this that a slow speed electron can pass near or thru the argon atom with less effect

on its motion than that experienced by a higher speed electron.

The reciprocal of α is the mean free path of the electron in the gas. By observing the effect of the mean free path of the electrons in the gas on the space charge about a hot filament, Minkowski and Sponer[4] predicted the same phenomenon in krypton and xenon that was observed in argon. The maximum of α for argon, krypton and xenon occurred at 13.2, 11.3, and 6.4 volts respectively.[5] The corresponding values of α at the maxima were 80, 100, and 140. sq cm per cu cm of gas. This is in each case about four times the kinetic theory value for α. G. Hertz[6], by a method similar to that used by Mayer, checked this unusual behavior of argon gas. Hertz kept his path length constant and changed the pressure of his gas.

From observations on the diffusion of slow speed electrons thru gases, Townsend and Bailey[7] also obtained data on the mean free path of electrons in argon. They found that the value of α decreased from its maximum at .4 volts and then increased as the voltage was lowered. By observing the effect of gases in a magnetron tube on the current to the plate, R. N. Chaudhuri[8] also found very long mean free paths for slow speed electrons in argon.

The purpose of the experiment described in the following pages, was to confirm the extraordinary behavior of electrons in argon and to see if the same or other characteristic phenomena could be found in other gases.

APPARATUS

The apparatus used for the study of this phenomenon, Fig 1 , was made of copper, silver soldered together. The filament, F, which was the source of electrons, was made of a spiral of tungsten wire. It was usually operated at 1.2

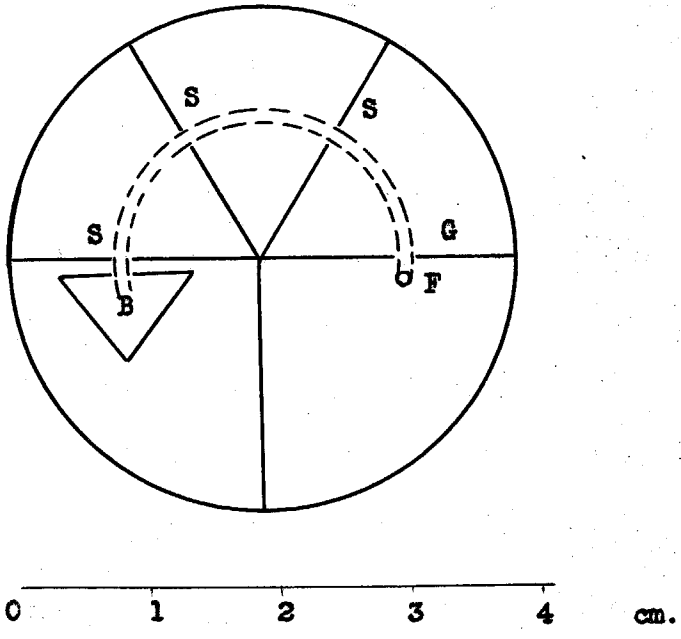


Fig 1

amperes when the voltage drop was about 4 volts. The filament was lighted by a storage battery which was maintained at a negative potential with respect to ground. The filament was placed 1 mm from the grid G which consisted of a row, 1 cm long, of 1 mm holes. The other slits S_1, S_2 and S_3 were rectangular, 1mm wide and 1 mm high. The slits were made so that their centers were on a circle 1cm in radius. The slits grid and enclosing box were silver soldered together and connected to ground. A microammeter, placed in the circuit of the battery that maintained the filament at a negative potential, measured the total emission of the filament. The reading of this microammeter, M, was taken as a measure of the electron stream that went around thru the slits. The electrons that reached the box B at the end of the path went to ground thru a Leeds and Northup type R galvanometer, sensitivity 2,500 megohms. The reading of the galvanometer, G_1, was taken as a measure of I_1, the intensity at the end of the path. The path length was 3.2 cm. The magnetic field that bent the electron stream into the circular path was produced by a solenoid, 15 cm in diameter and 30 cm long. A current of one ampere produced a field of 19 gauss at the center of the solenoid.

Pyrex glass was used in the construction of the glass apparatus so that the copper apparatus could be baked out to

450 degrees. The vacuum was obtained by two mercury diffusion pumps in series backed by an oil pump. In the part of the glass apparatus where there was a high vacuum, mercury cut-offs were used in place of stop-cocks so as not to introduce gases from the grease used on them. A McLeod gauge, reading to 1×10^{-5} mm of Hg, was used to measure the pressure. A liquid air trap was inserted between the mercury traps and pumps, and the part of the apparatus containing the copper. To admit small quantities of gas an apparatus was made as shown in Fig (2). By adjusting the height of the mercury column A, and lowering the column B, a known volume of 1 mm capillary tubing was filled with gas from the reservoir R. The pressure of the gas in R was usually about 1 or 2 cm of Hg. By raising the level of the mercury in B again, this amount of gas could be forced into the space above A which was connected to the high vacuum. In this way one could easily introduce enough gas to make the pressure in the apparatus of the order of 1×10^{-3} mm of Hg. By changing the Height of A and the pressure in R, the range of pressure produced by each operation can be extended indefinitely.

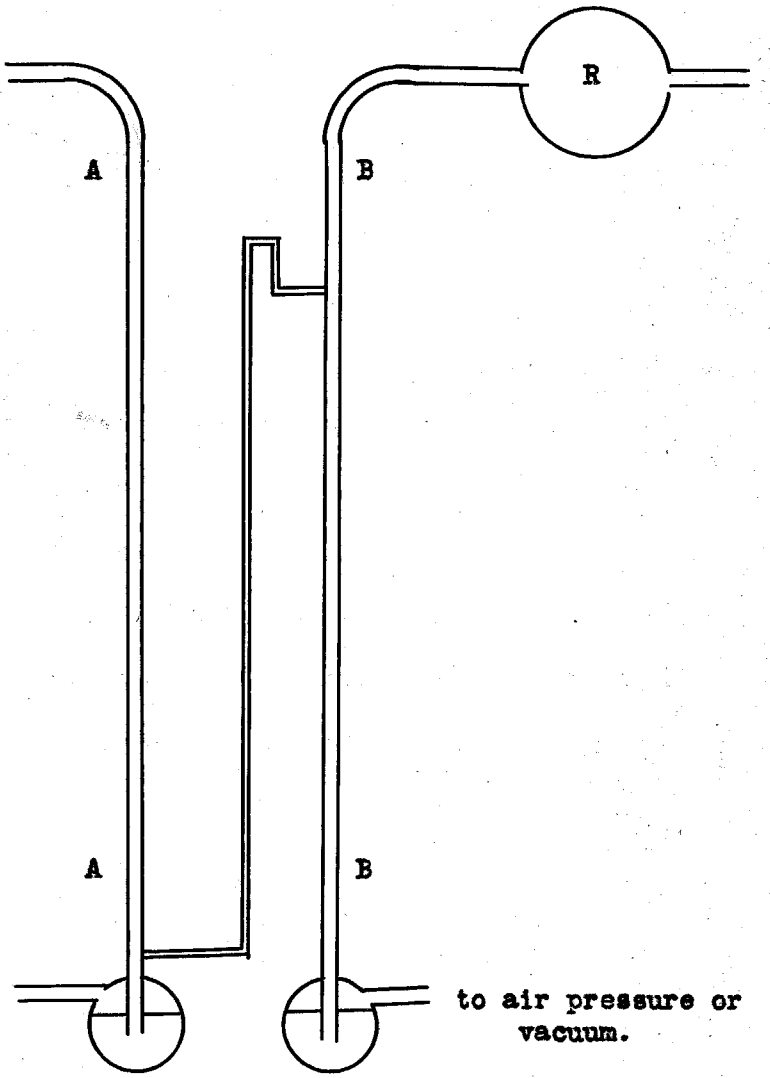


Fig 2

METHOD:

Introducing the reading of the microammeter M as being proportional to I_o and the reading of the galvanometer G for I , the value of α may be obtained from the following equation;

$$\alpha = \frac{1}{x\,(p_1 - p_2)} \log\left(\frac{M_1}{M_2} \cdot \frac{G_2}{G_1}\right)$$

x is kept constant and is equal to 3.2 cm. A high vacuum was generally used for p_2 so that it was essentially zero compared with a pressure of 2 to 5 x 10^{-3} mm of Hg used for p_1. M_1 and G_1 are the readings of the instruments for the pressure p_1 , and M_2 and G_2 for p_2.

Due to the voltage drop along the filament and to the temperature distribution of velocities, the values of the galvanometer deflections G, plotted against the magnetic field with a fixed accelerating potential, are as shown in Fig (3).

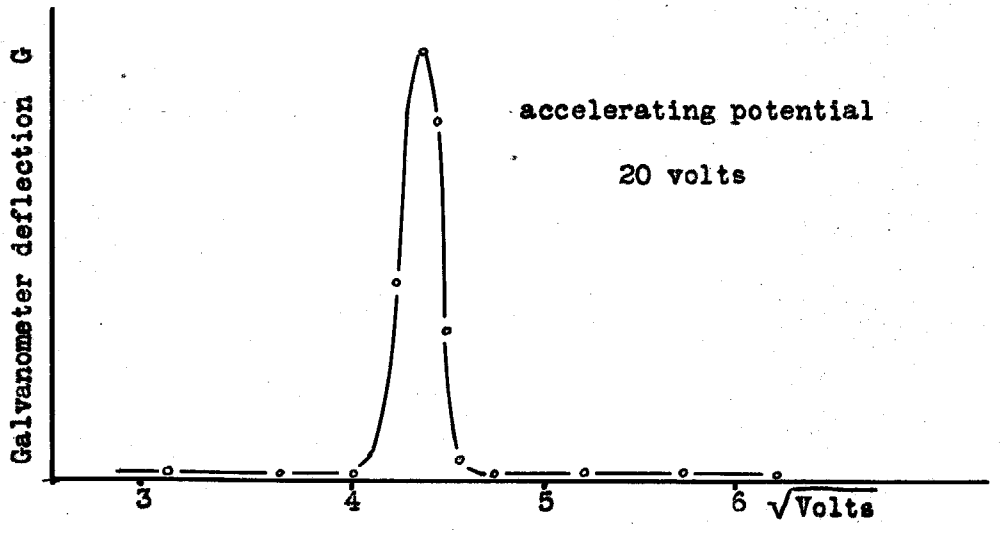


Fig 3

The maximum value of G is used in computing α in the above equation. The magnetic field was first fixed and this determined the velocity of the electrons that would go thru the slit system. The accelerating potential was then varied until the maximum deflection of the galvanometer was obtained. The readings of the meter M and the galvanometer G were then recorded. A small quantity of gas was then introduced, its pressure measured on the McLeod gauge, and the new readings of M and G recorded. By introducing more gas additional values for α could be obtained. If α was independent of the pressure of the gas used these values should all be the same. If the value of $\log \left(\frac{M}{G} \right)$ is plotted against the product of the pressure and the distance, then α will be the slope of the line connecting any two observations taken at different pressures. If α is constant when the pressure is varied then all of the points will lie on the same straight line. Fig (4) shows that the value of α is practically independent of the gas pressure.

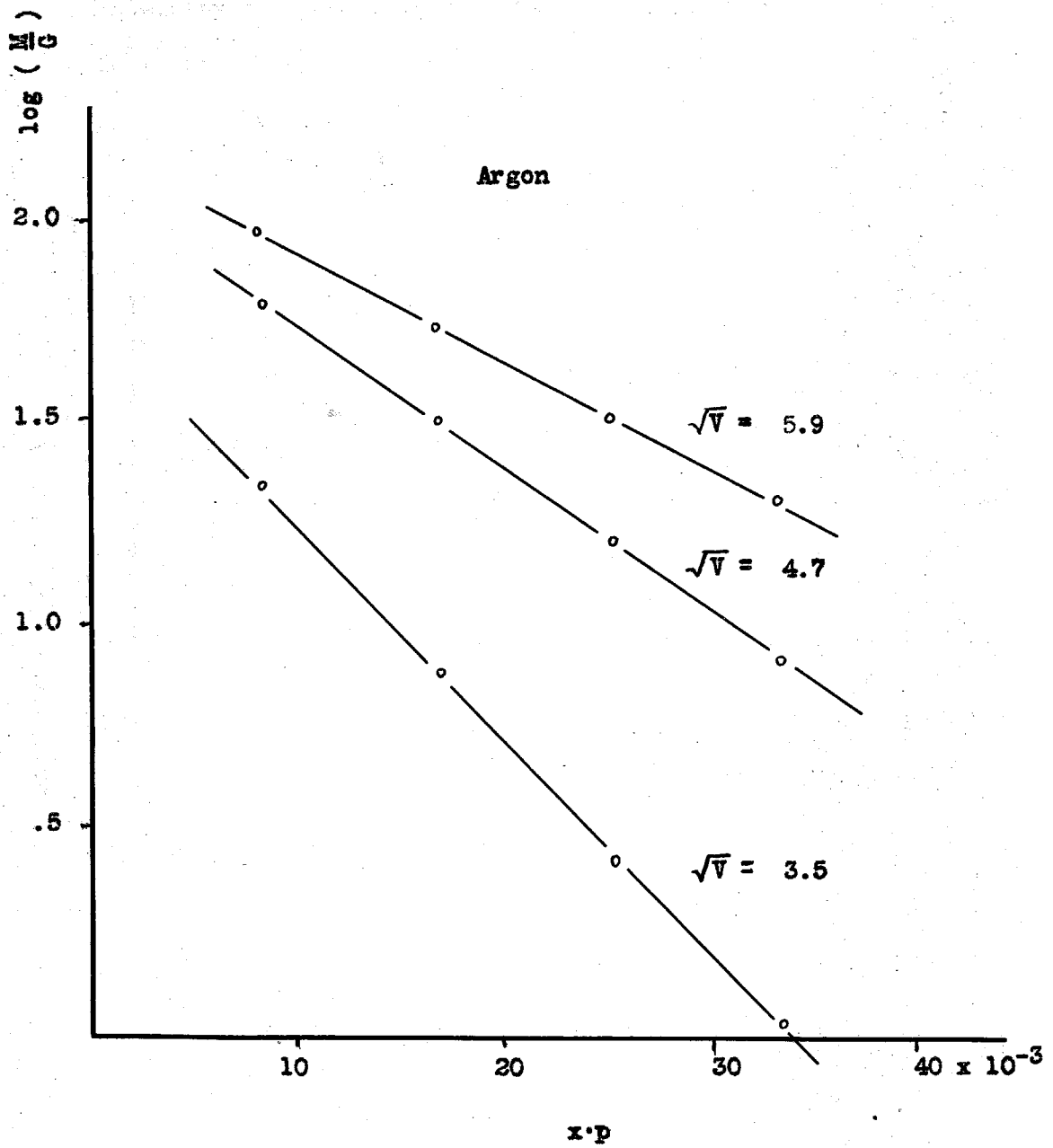

log (Mic
Argon
2.0
1.5
1.0
.5
$\sqrt{V}$ = 5.9
$\sqrt{V}$ = 4.7
$\sqrt{V}$ = 3.5
10
20
30
40 x 10^{-3}
x·p

Fig 4

Observations were also taken to see if the value of changed with the intensity of the electron stream. The intensity was varied by changing the temperature of the filament. Fig (5) shows that α remained practically constant when M was varied from 1 to 5 x 10^{-4} amperes.

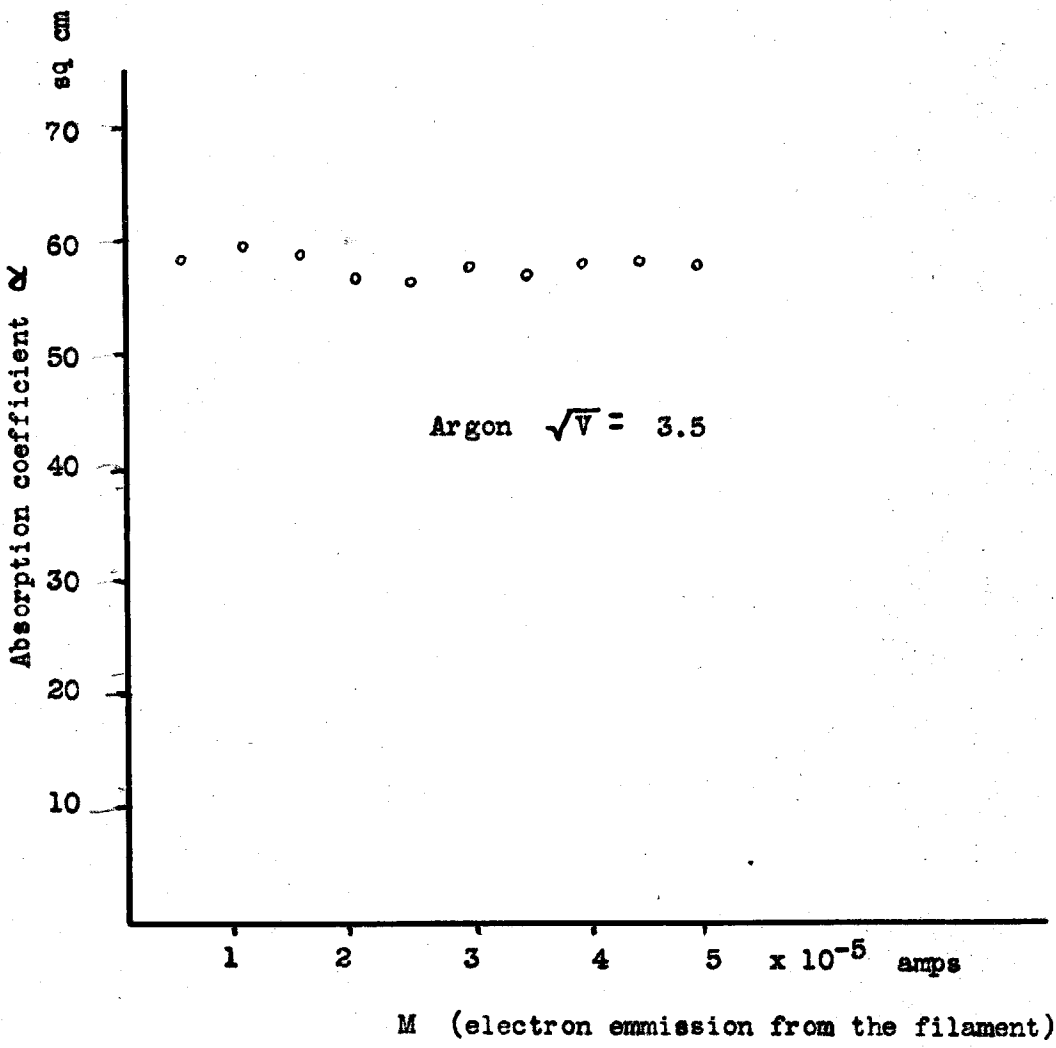


Fig 5

RESULTS

The gases prepared for this investigation were argon, helium, hydrogen, methane, carbon monoxide, nitrogen, carbon dioxide, acetylene, ethylene, ammonia, and cyanogen. The last five of these decomposed due to the tungsten filament and so could not be measured.

Argon was taken directly from a bulb secured from the General Electric Co. This argon was supposed to be 98% pure. The results of the measurements of α are shown in Fig (6). The dotted curve is for the values obtained by Ramsauer. The square root of the voltage used to accelerate the electron is plotted as the abscissa because the velocity of the electron in cm per sec is proportional to the square root of the voltage. Also the magnetic field used to determine the velocity is proportional to the square root of the voltage. The value of α was measured for velocities from 2 to 360 volts. The results obtained were found to check reasonably well with the results obtained by Ramsauer. The slowest speed electrons were again found to pass thru the gas with less deviation from their path than electrons of higher speed.

Helium was obtained from a tank received from the U. S. Government helium plant. It was further purified by allowing it to stand in the presence of a charcoal tube immersed in liquid air. The charcoal tube had previously

been heated to 450 degrees C for several hours. The results for helium are shown in Fig (7). Ramsauer's results are indicated by the dotted curve.

Methane, obtained from natural gas, was furnished by Dr. Glockler of the Gates Chemical Laboratory of this institution. It was further purified by liquefying with liquid air and then distilling. From the results shown in Fig (8) it can be seen that methane shows a somewhat similar variation of its value of α to that found for argon. The pressure of the gas did not change when allowed to stand in the presence of the hot tungsten filament. If the gas were decomposed by the temperature of the filament, an increase in the pressure should be observed.

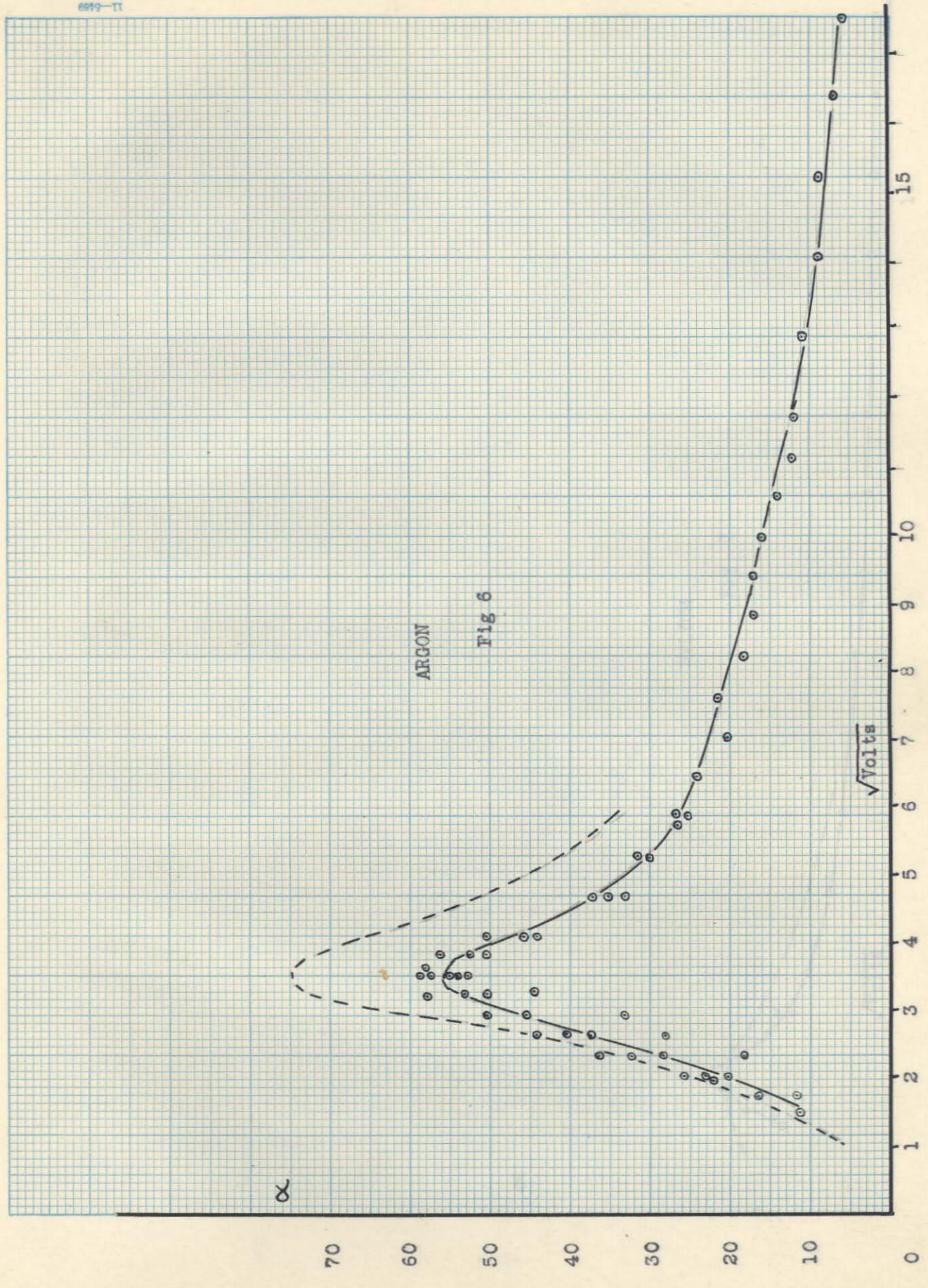
Electrolytic hydrogen was dried and further purified by charcoal cooled with liquid air. Fig (9) shows the values of α observed for hydrogen. The results are only in fair agreement with those of Ramsauer, shown with the dotted line. No maximum was observed in either case.

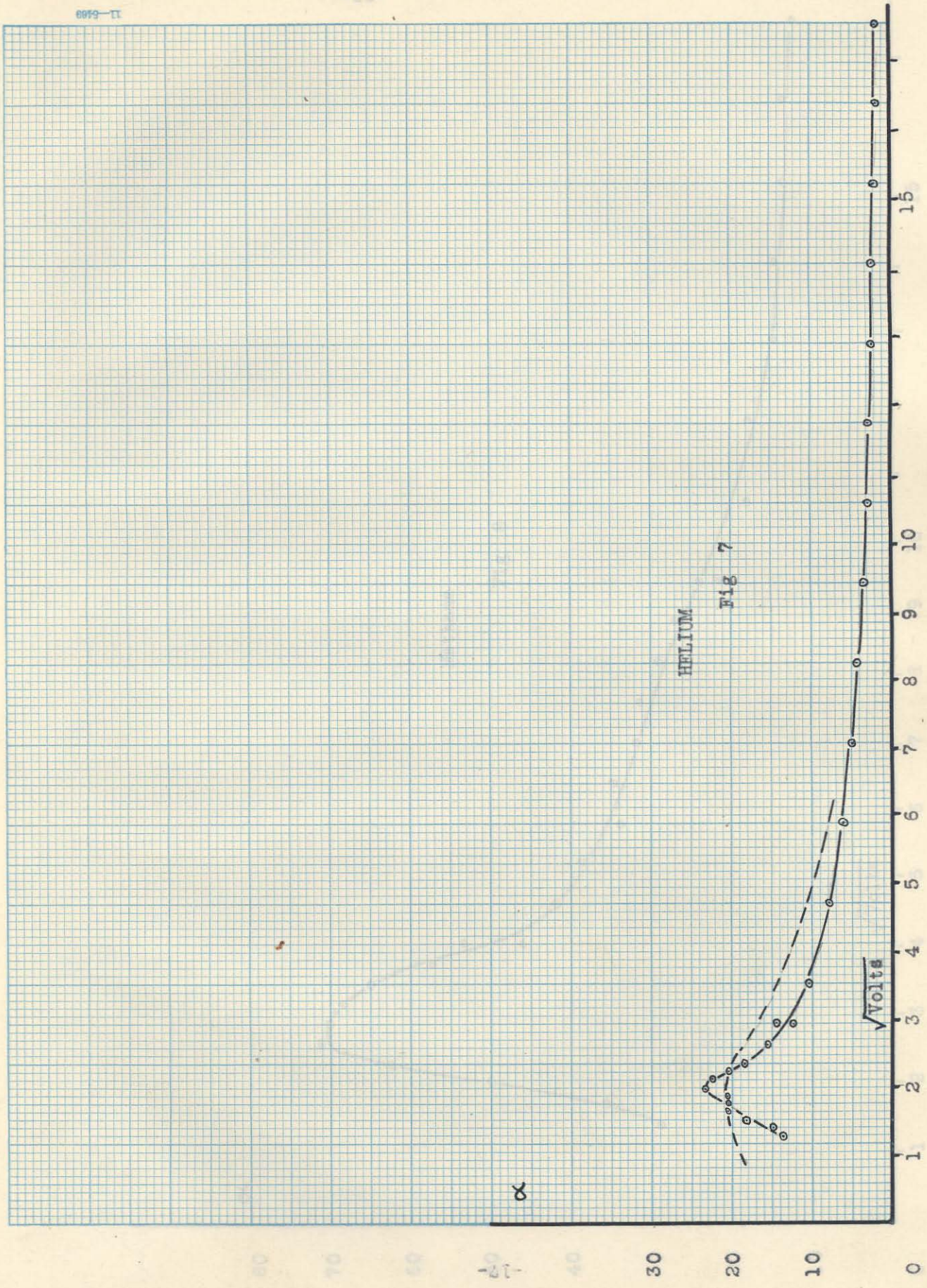
Nitrogen was prepared by the decomposition of ammonium nitrite, which on heating decomposes into nitrogen and water. A water solution of this was heated and the resulting gas dried by passing it thru a phosphorus pentoxide tube. The curve for nitrogen, Fig (10) differs from any

previous curve in that it has both a maximum and a minimum. the minimum occurs near the resonance potential of the nitrogen atom and the maximum near the ionization potential. The determination of the maximum and minimum points was, however, not sufficiently accurate to attach much significance to their occurence near these critical points.

Carbon monoxide was prepared by the decomposition of formic acid on being dropped into hot sulphuric acid. The curve of α for carbon monoxide, Fig (11), is seen to be almost identical with that obtained for nitrogen. The molecules of both of these gases consist of two atoms, each of which is supposed to have seven electrons. In the case of nitrogen the two positive nuclei have each seven positive charges. In carbon monoxide one nucleus has six positive charges and the other eight. The similarity of these two curves indicates that the deflection of the slow speed electron is determined chiefly by the field produced by the arrangement of the electrons in the molecule.

The rest of the gases tried, carbon dioxide, acetylene, ethylene, cyanogen and ammonia, were found to decompose, due to the effect of the hot tungsten filament. The decomposition was observed by an increase of pressure and by the temperature required to liquefy the gas before and after the filament had been heated. With an ice and salt mixture on the liquid air


ARGON
Fig 6
α
√Volts
0
10
20
30
40
50
60
70
1
2
3
4
5
6
7
8
9
10
15


HELIUM
Fig 7
α
√Volts
0
10
20
30
1
2
3
4
5
6
7
8
9
10
15

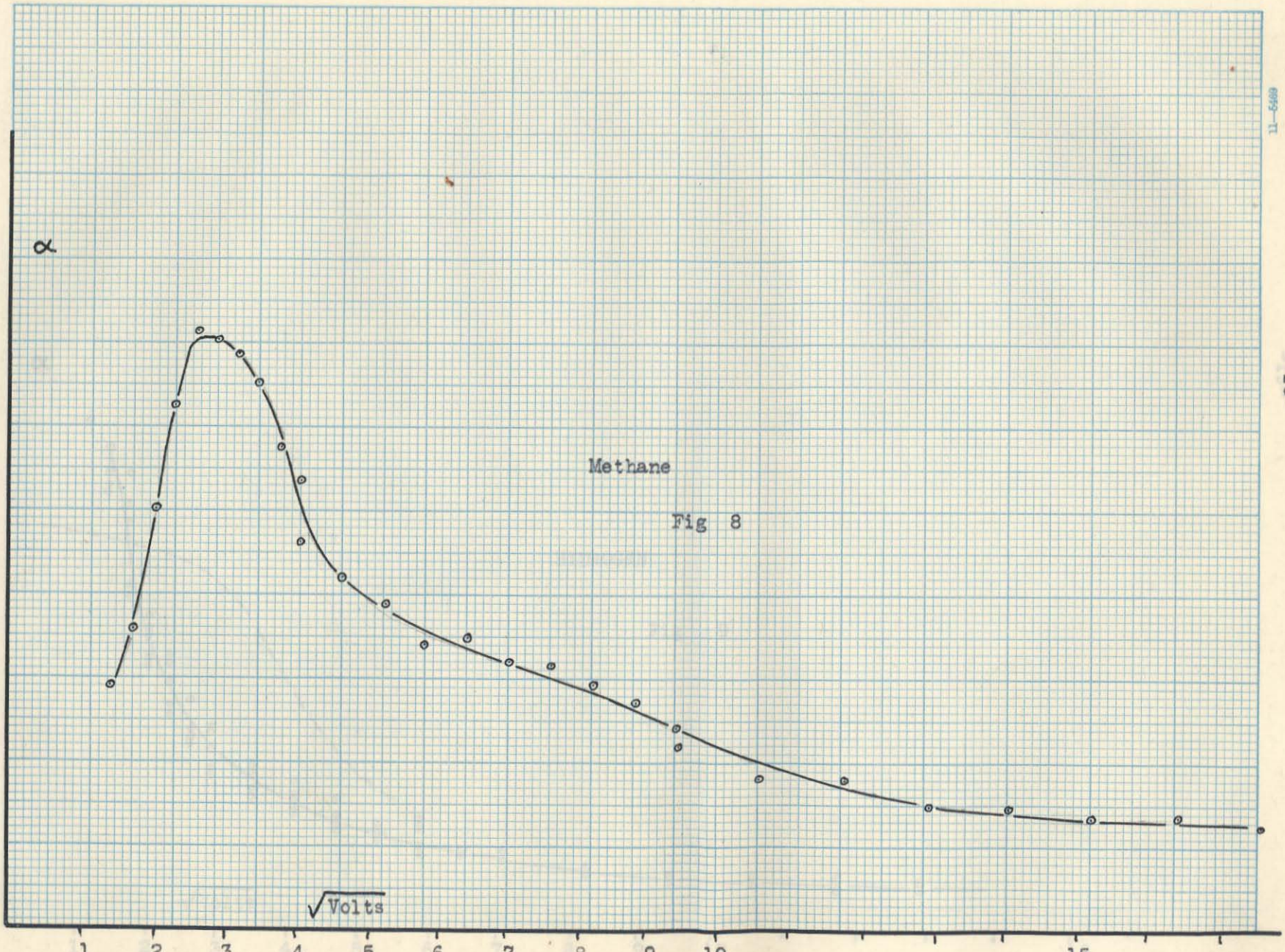


Fig 8

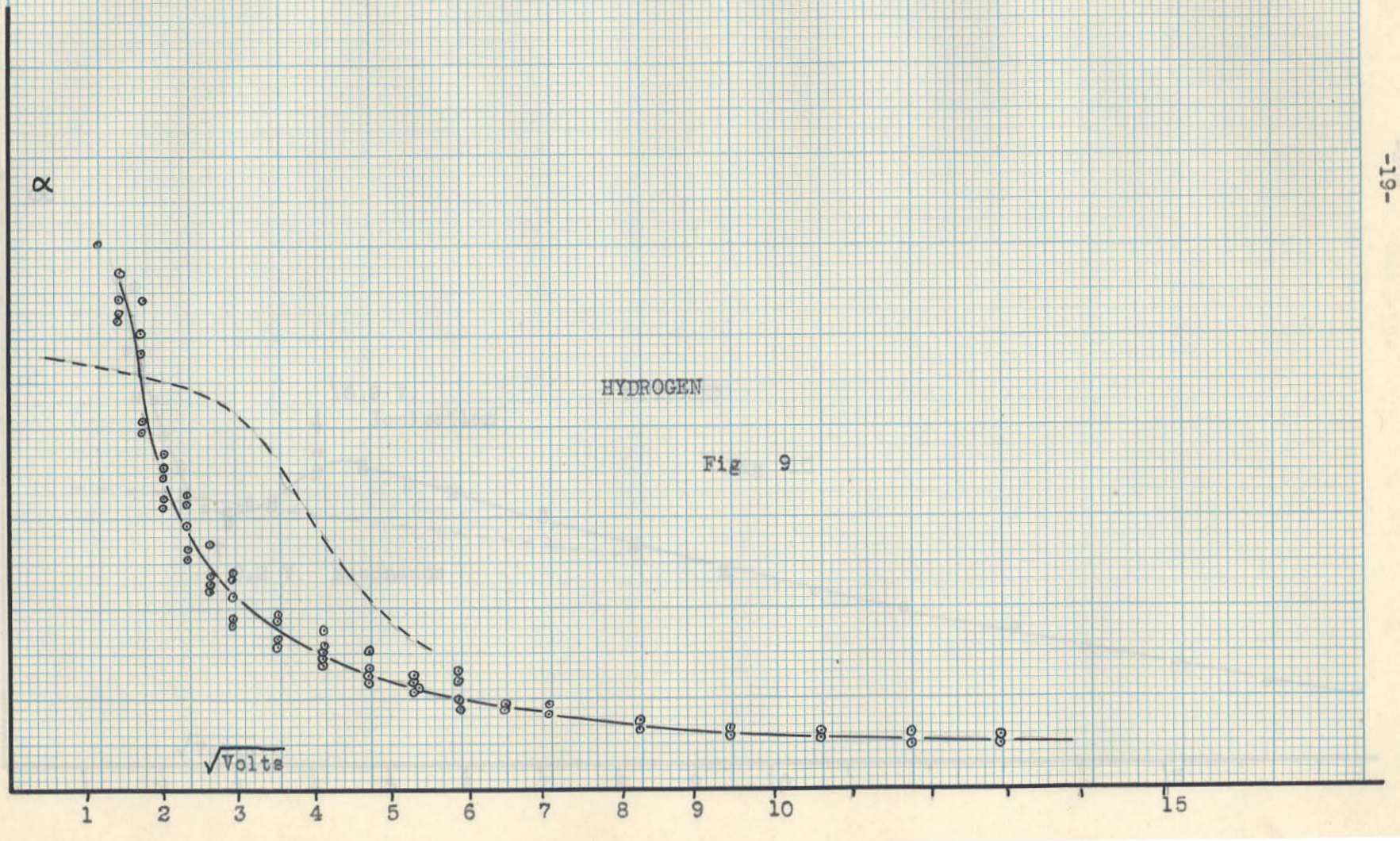
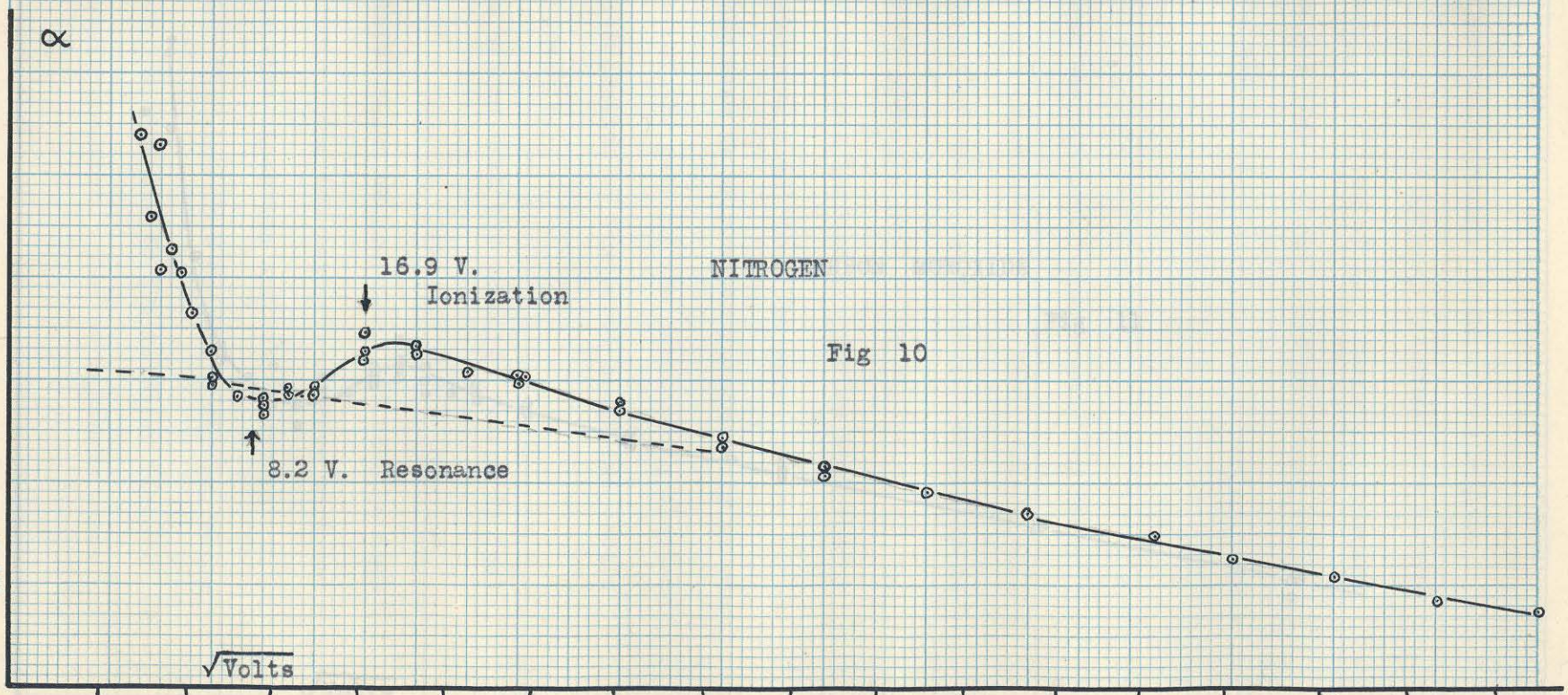


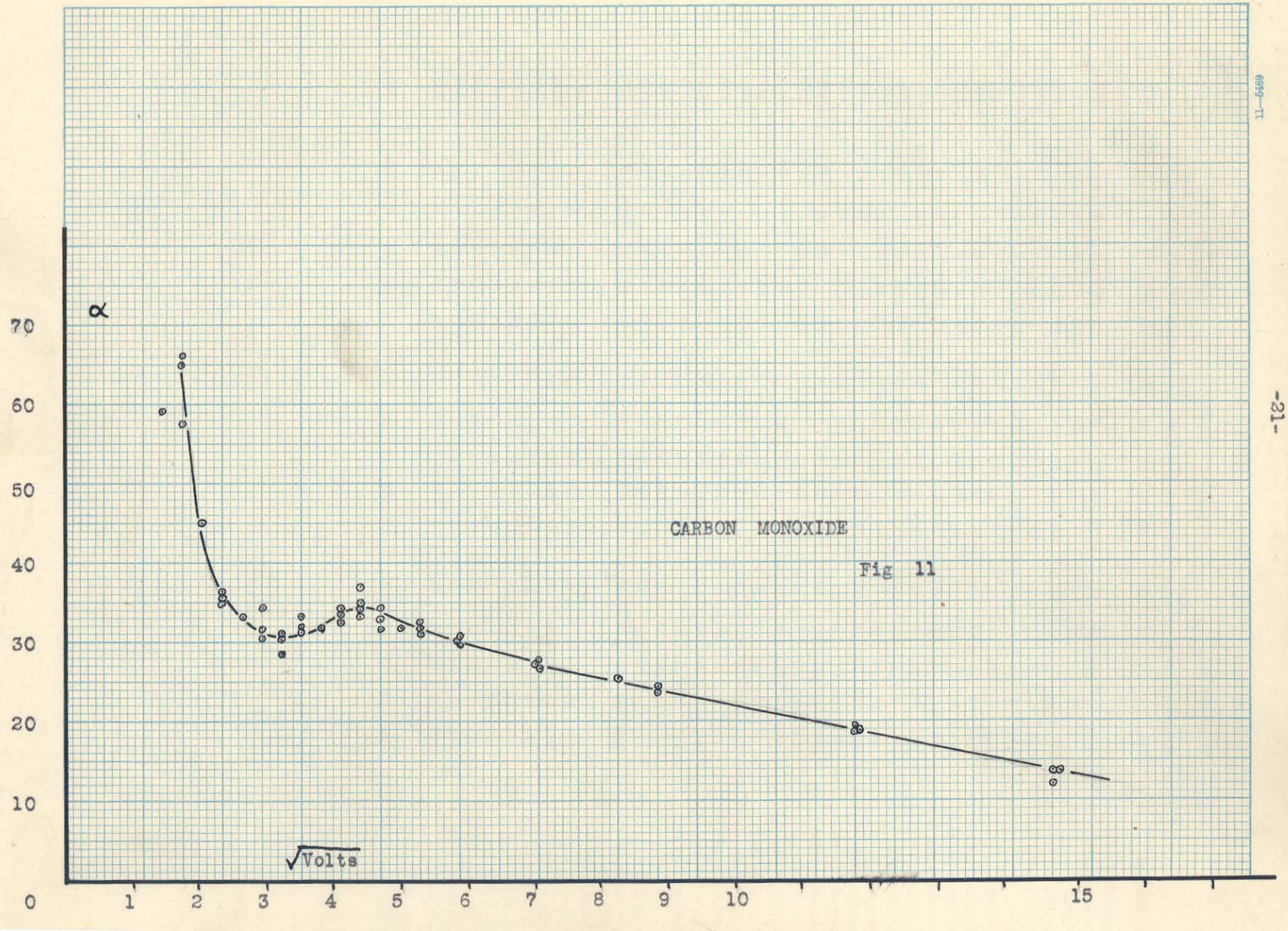
Fig 9

11-5469



NITROGEN

Fig 10


α
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
15
√Volts
CARBON MONOXIDE
Fig 11

trap, none of these gases condensed. Liquid air, however, condensed them all down from an initial pressure of 5×10^{-3} mm of Hg to less than 1×10^{-4} mm of Hg. After the filament had been run for a short time the gas could no longer be condensed with liquid air.

THEORY

The apparent absorption of electrons along their path as measured in this experiment is due to their interaction with the electric fields of the atoms in such a way so as to be deflected from their straight path. The variation of α then is a measure of how this interaction varies with the velocity of the penetrating electron. The exact nature of the electric fields in any atom is at present unknown, If it were known, the computation of the path of the penetrating electron and the resulting distribution of scattered electrons, would in most cases be impossible.

If one can assume that the negative charge in the atom is distributed in a uniform spherical shell then the deflection of the electron can be computed. If such an atom is placed in an electric field the negative charges will be drawn towards the positive direction and the positives towards the negative. The atom thus becomes a dipole, whose separation depends on the strength of the electric field it is in and on its dielectric constant. When an electron comes

near to an atom, it produces in the atom a separation of the charges proportional to the inverse square of the distance between the electron and the atom. The attraction of this dipole for the electron is proportional to its own separation and inversely proportional to the cube of the distance between the atom and the electron. Hence the force on an electron due to the polarization of an atom by the electron's own field, is inversely proportional to the fifth power of the distance between the atom and the electron. The potential energy of the electron in this field is,

$$P.E. = \frac{K-1}{8\pi n} \cdot \frac{e^2}{r^4}$$

K is the dielectric constant of the gas, n the number of molecules per cu cm, e the charge on the electron, and r the distance between the atom and the electron. In Fig (12), O is the center of the atom, p the perpendicular distance from the

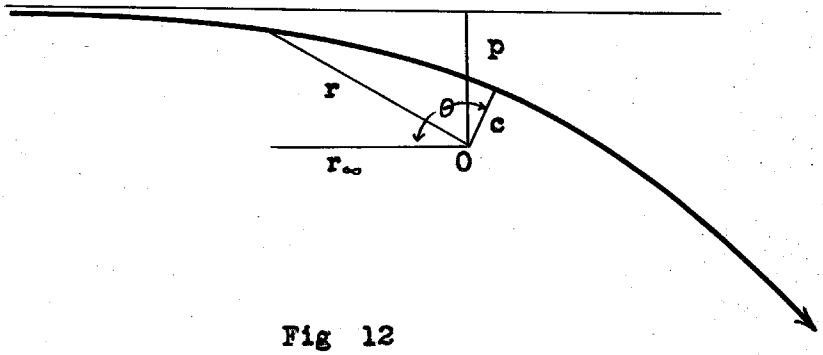


Fig 12

center of the atom to the continuation of the initial direction of the electron, r the distance of the electron from 0 at any time, c the nearest distance of approach of the electron to the atom, and θ the angle between c and the direction of r when r is infinite. By the application of the principles of dynamics the angle θ is found to be;

$$\theta = \int_0^{\rho_0} \frac{d\rho}{\sqrt{1 - \rho^2 - \frac{2A}{W p^4}\rho^4}}$$

In this equation $\rho = \frac{p}{r}$, $\rho_0 = \frac{p}{c}$, $\frac{A}{p^4}$ is the potential energy of an electron at a point where r is equal to p, and W is the initial kinetic energy of the electron or eV .

The solution of this elliptic integral gives θ as a function of the ratio of the initial kinetic energy to the potential energy at the distance p. Let this ratio be denoted by $R = \frac{W p^4}{A}$. In the apparatus used for this experiment a deflection of θ equal to $\pi + .06$ radians, as a reasonable estimate, will throw the electron out of the path. This corresponds to a value of $R = 2$. All electrons with an R greater than this will suffer a smaller deflection and will reach the end of the path. Those electrons with an R less than 2 will suffer a greater deflection and will not reach the end of the path. The value of the effective atom radius squared is p^2 or

$$p^2 = \sqrt{\frac{R A}{W}}$$

Introducing the values of A, R, and W, using the data for nitrogen i.e. $(K-1) = 6 \times 10^{-4}$: $n = 2.7 \times 10^{19}$ $e = 4.77 \times 10^{-10}$: and $V = V/300$

$$p^2 = 10./\sqrt{V} \times 10^{-16}$$

The value of α corresponding to this, obtained from the equation; $\alpha = \pi p^2 N P$, where N is the number of molecules per cc at unit pressure and P the pressure, is

$$\alpha = 224/\sqrt{V}$$

The relation between the computed curve and the observed curve can be seen in Fig (13). For hydrogen the constant 224 is replaced by 150. The theoretical curve gives values of α about twice the observed values in hydrogen. If 60 is used in place of the 150 a good agreement can be obtained, Fig (14).

From this theory the value of α should never decrease with decreasing velocity of the penetrating electron. It can be shown that any attracting field that is independent of the orientation of the atom will give a similar curve. For an inverse square attraction $\alpha = \text{const.}/V^2$, inverse cube $\alpha = \text{const.}/V$, and for an inverse fifth power $\alpha = \text{const.}/V^{\frac{1}{2}}$. The inverse square and the inverse fifth attracting fields are the only two in which it is physically possible that the field be independent of the orientation of the atom. F. Zwicky[9] has carried thru a

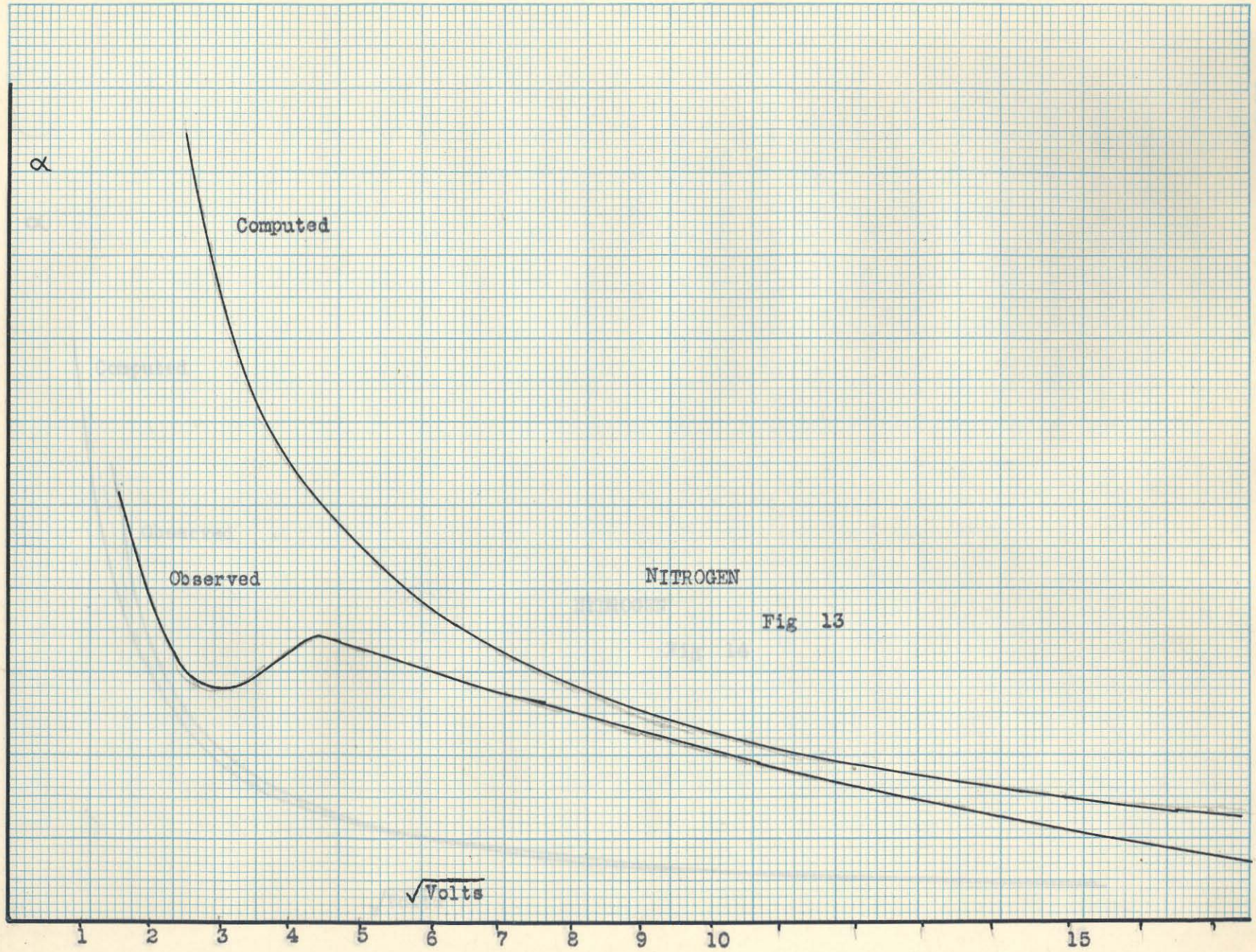
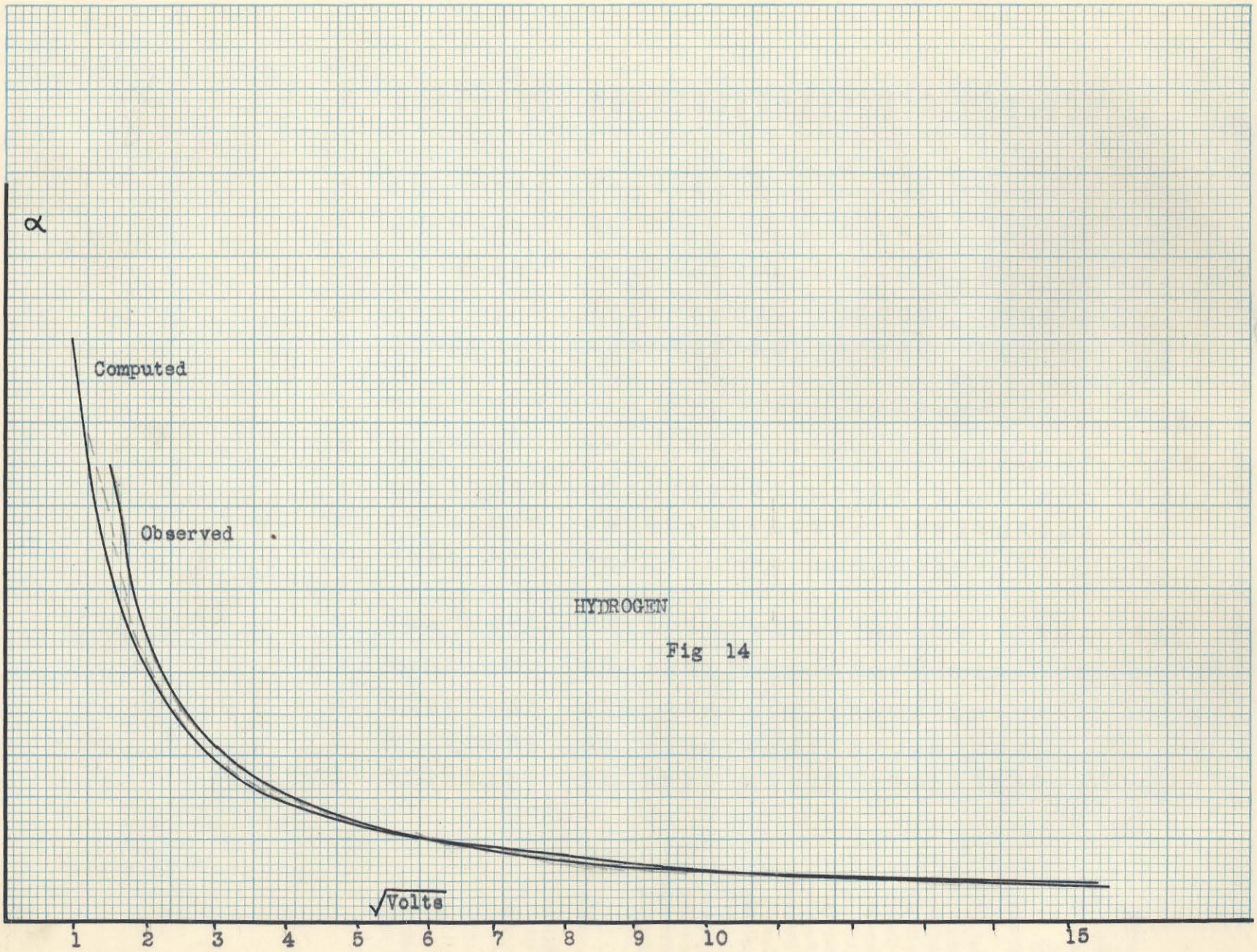


Fig 13


α
80
70
60
50
40
30
20
10
0
Computed
Observed
HYDROGEN
Fig 14
√Volts
1
2
3
4
5
6
7
8
9
10
15

similar computation and has obtained the same results. Any theory of a uniform attracting field results in an infinite value of α at zero velocity. Due to the small intensity of the electron stream, measurements could not be taken below 1.5 volts. Before a complete theory can be proposed more accurate measurements must be made on the variation of α in the region from 1 volt to nearly zero.

F. Hund[(vo)] has proposed an explanation based on the quantum theory. He proposes that an electron whose kinetic energy is less than the amount of energy it would radiate if it were allowed to suffer its classical acceleration towards the nucleus, will not radiate but will continue undisturbed on its path. This explanation is suitable for the noble gases but will not explain the curves obtained for nitrogen and carbon monoxide.

SUMMARY

The absorption coefficients for electrons in argon, helium, hydrogen, nitrogen, methane and carbon monoxide were measured for velocities from 2 to 360 volts. The results of Mayer and Ramsauer were checked for argon and helium, both having a maximum value of α . Methane was found to be similar to these. Nitrogen and carbon monoxide gave nearly identical results, both having a maximum and a minimum in their values of α . The value of α for hydrogen increased steadily as the voltage was lowered. More accurate data at lower velocities will be necessary before a satisfactory explanation can be given.

References

(1) P. Lenard, Ann der Phys. 12 - 714 - 1903

(2) H. F. Mayer, Ann der Phys. 64 - 451 - 1921

(3) C. Ramsauer, Ann der Phys. 64 - 513 - 1921

(4) Minkowski and Sponer, Zeit f Phys. 15 - 399 - 1923

(5) C. Ramsauer, Jahrb.d. Rad. u. Elek. 19 - 345 - 1923

(6) G. Hertz, Proc. Amsterdam Acad. 25 - 80 - 1922

(7) Townsend and Bailey, Phil. Mag. 44 - 1033 - 1922

(8) R. N. Chaudhuri, Phil. Mag. 46 - 461 - 1923

(9) F. Zwicky, Phys. Zeit. 24 - 171 - 1923

(10) F. Hund, Zeit. f. Phys. 13 - 241 - 1923