The Specific Probable Ionization of Electrons Observed with a Wilson Cloud Chamber

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The specific probable ionization of electrons has been measured for the energy range in which it is a rapidly varying function of velocity by counting the droplets along cloud-chamber tracks. The electron momenta have been determined by the use of a magnetic field perpendicular to the direction of photography, permitting counting along appreciable lengths of the helical tracks of slow electrons. The dependence of the measured specific ionization upon velocity agrees within the experimental uncertainty with that predicted by the Bethe-Bloch theory.

The ionization in the vapor has been determined experimentally, permitting the determination of the minimum ionization in the dry gases at standard conditions as 46.1 ± 2.2 ions per cm in air, 6.48 ± 0.34 in hydrogen, 8.13 ± 0.51 in helium, and 53.1 ± 2.8 in argon, where the statistical probable errors are indicated. These values are compared with the average ionization found for cosmic-ray mesons by Hazen and Skolil. The theoretical minimum rates of energy loss divided by these values give values of the average energy loss per ion pair of 31.2 ± 1.5 ev for air, 37.2 ± 2.0 for hydrogen, 26.0 ± 1.6 for helium, and 27.9 ± 1.5 for argon.

I. INTRODUCTION

THE modern theory of energy loss by charged particles through ionization and excitation[1] is in agreement with many direct measurements of the range and energy loss of energetic particles; however, many cloud-chamber measurements of specific ionization show poor agreement with the theory. In particular, there have been no adequate cloud-chamber data on the specific probable ionization of particles in the low-momentum range in which the velocity and specific ionization vary rapidly. This paper reports measurements of the specific ionization of electrons with energies of several thousand to several hundred thousand electron volts, made to obtain information for improving the accuracy of cloud-chamber measurements of particle velocity.

These measurements are of the "specific probable ionization" made by counting droplets along diffuse tracks,[2] omitting droplets associated with clusters larger than a certain arbitrarily chosen size. Thus the probable ionization is related to the energy loss in the less energetic collisions only. Measurements of the specific probable ionization of cosmic-ray particles (with high momenta where the specific ionization does not change rapidly with momentum) have been made by Corson and Brode,[2,3] Sen Gupta,[4] Hazen,[5] Skolil,[6] and Hayward.[7] In the lower-momentum region measurements have been made by Corson and Brode,[3] Wilson,[8] and Beekman,[9] but these measurements are either limited in scope or show disagreement with the theory and other work.

Cloud-chamber measurement of ionization requires not only counting the droplets but also knowing the efficiency with which ions are represented by droplets along each particle track. Separating positive and negative ions permits determining this condensation efficiency from measurements[10] of the manner in which its dependence on expansion ratio and vapor composition differs for positive and negative ions. The technique of separating the positive and negative ions for this purpose was implicit in the original work of Wilson and has been used in the measurements of specific probable ionization by Hazen and his co-workers.[5–7] The present work includes an experimental determination of the ionization in the water-alcohol vapor used. This gives directly the value of vapor correction required to obtain the ionization in dry air, hydrogen, helium, and argon.

II. EXPERIMENTAL METHOD

1. Measurement of Momentum

The momentum of each electron was determined from the radius of curvature of the track due to a magnetic field. This radius must be small compared with the scattering "radius of curvature" due to the multiple collisions of the electrons with the molecules of the gas. Decrease of this scattering radius of curvature with decreasing electron velocity requires that very small magnetic radii of curvature be used in measuring the momenta of low-energy electrons. It follows that scattering and the required magnetic field together so bend slow electron tracks that they appear in the usual photographs with camera axis parallel to magnetic field as a confusion of overlapping small arcs.

To facilitate accurate curvature measurement and to provide adequate lengths of track free from overlapping for droplet counting, the electrons were intro-

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[1] See, for example, B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 240 (1941), and references given there.
[2] See, for example, R. B. Brode, Revs. Modern Phys. **11**, 222 (1939).
[3] D. R. Corson and R. B. Brode, Phys. Rev. **53**, 773 (1938).
[4] R. L. Sen Gupta, Proc. Natl. Inst. Sci. India **9**, 295 (1943).
[5] W. E. Hazen, Phys. Rev. **65**, 259 (1944) and **67**, 269 (1945).
[6] L. L. Skolil, Phys. Rev. **70**, 619 (1946).
[7] E. Hayward, Phys. Rev. **72**, 937 (1947).
[8] C. T. R. Wilson, Proc. Roy. Soc. (London) **A104**, 192 (1923).
[9] W. J. Beekman, Physica **12**, 534 (1946).
[10] C. E. Nielsen, Dissertation, University of California, Berkeley 1941 (unpublished) and Phys. Rev. **61**, 202 (1942).

duced with a component of momentum parallel to the field, and the tracks were photographed from a direction perpendicular to the magnetic field. This method[11] permitted each turn of the helical track to be seen and counted separately, the projection in the plane of the picture being sinusoidal. The components of momentum parallel and perpendicular to the field are both obtainable from the one picture.

The magnet[12] consisted of two water-cooled coils spaced to permit illumination and photography between them, with properly proportioned iron rings inside each coil and iron bars outside parallel to the coil axis. This iron slightly increased the strength of the field and greatly improved its uniformity. As used at about 1300 gauss, the field was uniform to within one percent throughout most of the volume.

The radius of curvature ρ that the track would have if it were perpendicular to the field was calculated separately for each half-loop of the track from the radius of the helix and the axial length of the half-turn. Thus it was possible to obtain a larger number of determinations of the momentum of each of the slower tracks to offset the greater errors entering from scattering.

2. Measurement of Ionization

The cloud chamber designed for use with this magnet expanded axially in the direction of the horizontal magnetic field, as indicated in Fig. 1. To permit undistorted photography from above, the working volume was hexagonally shaped with alternate sides of plate glass; the two lower windows were used to illuminate the chamber. The source of illumination was a single 900-watt incandescent projection lamp flashed momentarily when taking the picture at a voltage 23 percent above its rated value. Panes of heat-absorbing glass were placed in the light paths, and the hot air from the lamp was removed with a small blower. A continuous sheet of water was circulated between the lower chamber windows and outer panes of glass. The chamber was further protected from the heat generated in the magnet by water cooling of all the metal sides and the end.

The chamber operation was controlled entirely by a mechanical cam system which also rotated a sample of radioactive phosphorous past a thin aluminum window in the end wall of the chamber opposite the diaphragm. The source was opposite the window approximately 0.02 second before the resulting ions along the electron tracks were immobilized by the formation of drops, thus allowing the necessary diffusion of the ions to permit counting of the drop images. The positive and negative ions were separated by a small residual electrical clearing field perpendicular to the axis of the magnetic field and in the plane of view, so that the drops formed on the positive and negative ions formed two parallel but distinct tracks. All tracks containing less than one-fifth the number of positive track drops in the negative track were discarded. Measurements made[10] of the dependence of condensation efficiency for positive and negative ions upon vapor composition show that, even for a vapor composition differing considerably from that in equilibrium with the water and 75 percent ethanol liquid used, this should ensure that essentially all of the positive ions will be represented by drops.

The tracks were measured directly from the original negative, using a microscope equipped with a stage movable in any two perpendicular directions by micrometer screws. The drops were counted with the aid of a key and message register, and the coordinates of each peak of the sinusoidal projection of the track were recorded as it was reached. An arbitrary length of track was included in each cluster count. The largest clusters included in the track count contain 25 drops in addition to the average ionization found along adjacent sections of track. This selection corresponds to the exclusion of ionization events in which the energy transferred is greater than 600 to 800 electron volts, the exact value depending upon the energy expended in producing one ion pair in the particular gas and vapor mixture.

3. Elongation Correction

The axial distances measured required correction for the distortion of the track produced by the expansion of the chamber. This expansion stretched the helix of ions, increasing the apparent momentum of the track and reducing the apparent ionization. With low operating pressures, tracks entered the chamber after the beginning of the expansion, necessitating measurements of track age and expansion rate to permit determination of the amount of elongation. The ages of the tracks were obtained from measurements of the separation of the positive and negative ion tracks together with data on the mobilities of the ions in the gas-vapor mixture used obtained with a pulsed x-ray source. Measurements of the rate of expansion of the chamber were made for each pressure used by fitting one of the small windows in the wall of the chamber opposite the diaphragm with a pressure-sensitive switch.

4. Vapor Correction

Pictures were taken with widely varying pressures of hydrogen in the chamber, permitting determination of the ionization in the hydrogen and the vapor separately on the assumption that there is no interaction between the gases in the chamber. An interaction such as the ionization of vapor molecules by metastable excited states such as are known to exist in helium should increase the apparent ionization in the gas by an amount proportional to the pressure of the gas only, if the vapor correction is made as indicated below. The present results would then be directly applicable

[11] C. E. Nielsen, Phys. Rev. **70**, 444 (1946).
[12] C. E. Nielsen, Phys. Rev. **70**, 450 (1946).

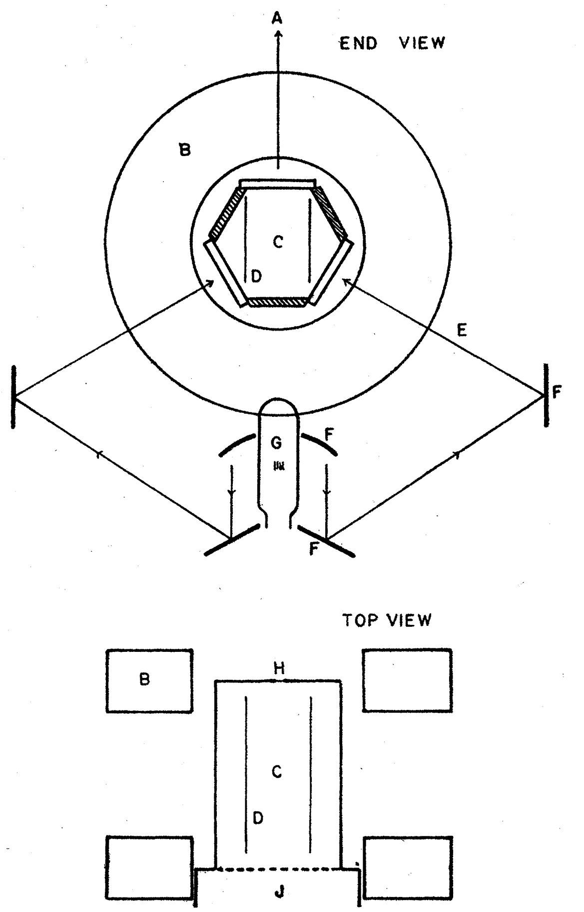

FIG. 1. Arrangement of magnet and cloud chamber. A, camera; B, magnet coil; C, working volume of chamber; D, clearing field electrode (grid of fine wires); E, incident illumination; F, mirror; G, lamp; H, thin window for admitting electrons; J, expansion diaphragm, etc.

to cloud-chamber experiments involving other pressures of the same gases and vapor, even if they should not be applicable to the ionization in dry gases.

5. Miscellaneous Corrections

(a) *Temperature*

Since the water-alcohol vapor was in equilibrium with its liquid phase, its pressure was very sensitive to changes in the temperature of the chamber, requiring corrections of as much as three percent per degree C in the total ionization. The estimated probable error in measurements of the chamber temperature was 0.2°C.

(b) *Background*

Counts were made of arbitrarily chosen areas of the pictures that did not contain tracks to correct for the general drop background.

(c) *Resolution of Drop Images*

A correction for the superposition of drop images has been estimated on the assumption that two drops will be counted as one if the distance between their centers is not greater than their radius. The projected distribution of drops about the track axis was considered as that given by the normal error curve, neglecting the bunching effect of clusters. With this assumption the correction to the number of drops per cm on the photographic negative may be shown to be $0.60\ r^2 i_0^2/b$, where i_0 is the observed number of drop images per cm, r is the radius of the images, and b is the breadth of the part of the track that includes just half of the drops. Measurements of this breadth and of the drop diameter, usually 0.003 cm, were made for each track. In view of the small size of the correction (usually less than three percent) the bunching effect was not considered important, although in a few cases the correction for large clusters was calculated separately.

III. RESULTS

1. Ionic Mobilities in the Cloud Chamber

Approximate values found for the sum of the mobilities of the positive and negative ions in the gas and vapor mixture of the chamber are 5 $cm^2\ sec^{-1}\ v^{-1}$ in air at 13-cm pressure, 3.5 in helium at 47 cm, 25 and 9 in hydrogen at 14 cm and 43 cm, and 11 in argon at 13 cm. These values are intermediate between values to be expected[13] for the respective gases and for the alcohol vapor.

2. Dependence of Ionization upon Velocity

The results of the measurements of ionization are summarized in Figs. 2, 3, 4, and 5, in which the specific probable ionization I is plotted as a function of the velocity β in units of the velocity of light. For this purpose the tracks have been grouped together so that each point represents from one to five tracks. The values for I and β have been averaged with weights chosen on the assumption that the chief uncertainty is due to the statistical error in the counting. The vertical lines through the points in the figures are the probable errors estimated from the number of drops counted. For this purpose the number of randomly occurring events is assumed to be 30 percent of the number of ion pairs in the tracks, which corresponds approximately to the actual statistical probable error observed in ionization measurements on a group of tracks for which the ionization was calculated separately for each half-turn. The probable error shown for β on a few of the points has been calculated from the scatter of the values obtained from successive half-turns of each track.

The solid curves shown in these figures represent the dependence of specific probable ionization on velocity

[13] J. J. Thomson, *Conduction of Electricity through Gases* (Cambridge University Press, Cambridge, 1928), third edition, Vol. 1, pp. 123–5.

given by the Bethe-Bloch theory.[1] The theory gives the "probable" rate of energy loss by a charged particle excluding the larger energy transfers. This energy loss divided by the average energy loss per ion pair w gives the number of ions per cm I not associated with energy transfers greater than mw, when m is the largest number (net) of ions in a cluster included in a drop count. For a gas the expression may be written

$$I = C/\beta^2[k + \ln\{\beta^2/(1-\beta^2)\} - \beta^2],$$

where the constants are $C = 24.5(nZ/w)(p/T)$ and $k = \ln\{10^6 mw/I^2(Z)\}$, in which nZ is the number of electrons per molecule, w is the mean energy loss per ion pair in electron volts, p is the pressure of the gas in cm of mercury, T is the temperature in degrees Kelvin, and $I(Z)$ is the average ionization potential in electron volts. The values used here for $I(Z)$ are 17.5 electron volts for hydrogen,[14] 44 for helium,[15] and 11.5 Z for the other elements.[16] The values used for w are given in the first line of Table I with the addition of values of 31 for carbon dioxide and 30 for oxygen (thence 34 for carbon with the assumption indicated below). These values appeared the best available when the curves were plotted; the values of w for hydrogen, helium, and argon agree with the values of Gurney[17] as revised by Gray[18] and with the values of Stetter;[19] the other values are from Eisl[20] and Gerbes.[21]

For plotting this function, it has been assumed that the contributions to the ionization of the elements present in the vapor are simply additive, without regard to any effect of chemical binding. Gray[18] has presented some evidence that the stopping powers of water and ethanol may be calculated with a similar assumption. The ionization of a mixture may be represented by an equation of the same form, where $C = \Sigma_i C_i$ and $k = (\Sigma_i C_i k_i)/(\Sigma_i C_i)$, where C_i and k_i represent the values appropriate for each constituent. This is equivalent to assuming a mean value of w given by $1/w = (\Sigma_i p_i n_i Z_i/w_i)/(\Sigma_i p_i n_i Z_i)$, which has been used to obtain the value for carbon above.

In comparing the experimental points with the experimental curve, it should be noted that the indicated "probable errors" in the ionization are not true probable errors in the sense of describing the width of a normal distribution, since the tail of the actual distribution is increased by the production of energetic secondaries. The suggestion at a few points of a lower specific ionization than that predicted for slow electrons in air and argon is probably not significant because of the much greater scattering of slow electrons in these heavier gases. In particular, the point indicated for air by a cross represents the slowest electron in the group, since it was observed to stop in the gas of the cloud chamber. In contrast, with the lowest pressure of hydrogen used in the chamber, a somewhat higher-than-predicted ionization is found for an electron with an energy of only 14 kilovolts and a measured ionization of 16 times the minimum, and other slow electrons in hydrogen and helium show an ionization in good agreement with the theory. There is thus no significant difference between observed and theoretical velocity dependence of ionization. Agreement in ordinate indicates that, except perhaps for helium, the values of w used in plotting the curves are close to those implied by the data.

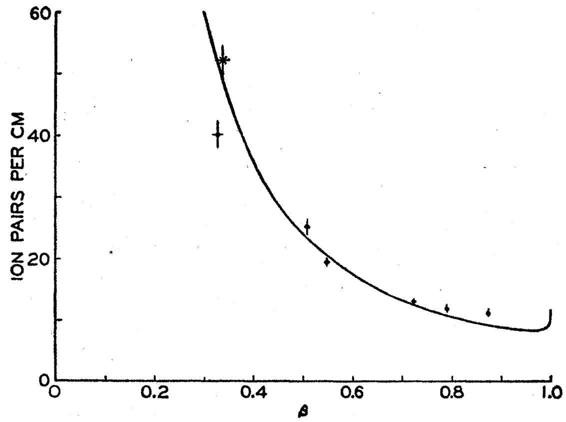

FIG. 2. Specific ionization in air and vapor at a pressure of 13.6 cm and a temperature of 14°C.

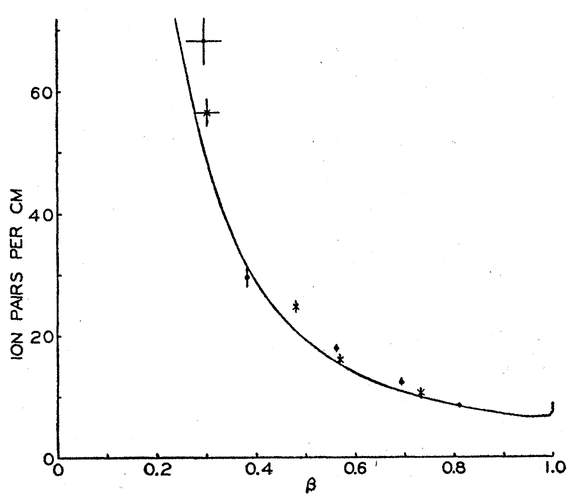

FIG. 3. Specific ionization in helium and vapor at a pressure of 51.0 cm and a temperature of 14°C. Crosses represent points obtained with commercial (96 percent guaranteed purity) helium; other points obtained with purified helium furnished by Department of Chemistry, University of California.

[14] H. A. Bethe, Ann. Physik. **5**, 325 (1930).
[15] E. J. Williams, Proc. Cambridge Phil. Soc. **33**, 179 (1937).
[16] F. Bloch, Z. Physik **81**, 363 (1933); R. R. Wilson, Phys. Rev. **60**, 749 (1941).
[17] R. W. Gurney, Proc. Roy. Soc. (London) **A107**, 332 (1925).
[18] L. H. Gray, Proc. Cambridge Phil. Soc. **40**, 72 (1944).
[19] G. Stetter, Z. Physik **120**, 639 (1943).
[20] A. Eisl, Ann. Physik **3**, 277 (1929).
[21] W. Gerbes, Ann. Physik **30**, 169 (1937).

3. Ionization in the Vapor

The ionization in the water and ethanol vapor used in the cloud chamber was found from the data obtained with hydrogen in the chamber at total pressures of 14.3 cm, 46 cm, and 72.4 cm. To reduce the data taken at different velocities, the values of ionization have been reduced to the ionization to be expected at the minimum of the curve for the pressures and temperatures used, on the assumption that the ionization varies with velocity as predicted by the theoretical equation. This reduction is not very sensitive to the values chosen for w and $I(Z)$. The hydrogen data reduced in this way are shown in Fig. 6 in which the minimum ionization is plotted as a function of the partial pressure of hydrogen. The vertical lines through the points indicate the statistical probable errors in the weighted mean values of the ionization at each pressure, and the straight line has been fitted to the three points by the method

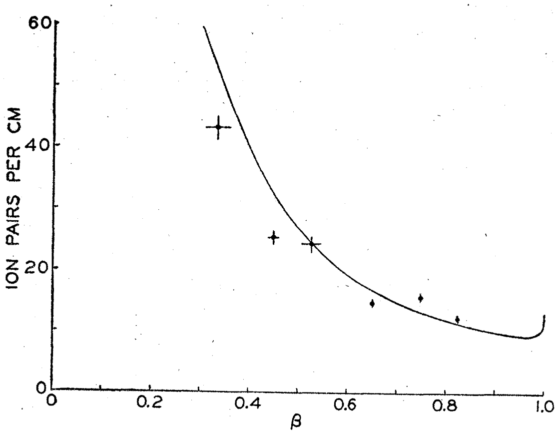

FIG. 4. Specific ionization in argon and vapor at a pressure of 13.5 cm and a temperature of 14°C.

of least squares. The intercept of the line with the ionization axis gives a value for the minimum ionization in the saturated vapor in equilibrium with the 75 percent ethanol and water liquid at 14°C of 2.36±0.15 ion pairs per cm. The value calculated from the theory as indicated above is 2.46 ion pairs per cm, in which the greatest uncertainty should be in the choice of values for w.

This agreement may be contrasted with the result of Beekman,[9] which indicated a specific ionization in the vapor, over 60 percent alcohol and water, of about two and one-half times the expected value, while he found an ionization in air of only about two-thirds of the values found by Hazen and ourselves. Beekman's work was done by a similar method but with a much smaller part of the total ionization occurring in the vapor, and apparently without a rigorous criterion for the condensation efficiency of his chamber. Examination of his published data suggests that drops in his denser tracks may not have been adequately resolved for counting, and this would reduce the apparent fraction of the ionization occurring in the gas.

4. Minimum Ionization in the Dry Gases

The minimum ionization in hydrogen obtained from the slope of the line in Fig. 6, reduced to 76-cm pressure and 0°C, is 6.48±0.34 ion pairs per cm. For the other gases subtraction of the experimental value for the ionization in the vapor from experimental values similarly reduced to minimum ionization by means of the theoretical equation gives values for the dry gases which, when corrected to 76-cm pressure and 0°C, are 46.1±2.2 ion pairs per cm for air, 8.13±0.51 for helium, and 53.1±2.8 for argon.

5. Average Energy Loss per Ion Pair

The ratios between the theoretical minimum rate of energy loss and the observed minimum specific ionization are shown in the second line of Table I. These may be regarded as experimental determinations of the average energy loss per ion pair w if one assumes the correctness of the theoretical velocity dependence used in making the reduction to minimum ionization. (This is not appreciably affected by the choice of w because of the insensitivity of the curve to changes in the argument of the logarithm.) Recent electrically measured values[22,23] of w are presented in the third and fourth lines of Table I for comparison. A considerable variety of values for w appears in the literature, but some of the inconsistencies have been explained by measurements of the dependence of w upon the velocity of the particle producing the ionization, especially in air,[18] and of the dependence of w on the purity of the gas.[24] Thus the low value for helium in the present work may result from the ionization of vapor molecules by a metastable excited state in helium as suggested by Skolil,[6] but could

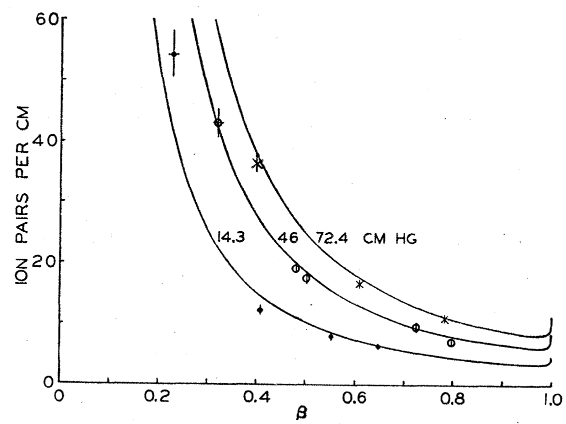

FIG. 5. Specific ionization in hydrogen and vapor at a temperature of 14°C.

[22] C. J. Bakker and E. Segrè, Phys. Rev. 81, 489 (1951).
[23] J. M. Valentine and S. C. Curran, Phil. Mag. 43, 964 (1952).
[24] W. P. Jesse and J. Sadauskis, Phys. Rev. 88, 417 (1952).

result from experimental error caused by the contamination of the helium-vapor mixture with a small amount of a more heavily ionizing gas, despite precautions to avoid such contamination.

The present values for w are influenced only slightly by the uncertainty in the value of the mean ionization potential $I(Z)$. A comparison of these values used with more recent values[25] shows a maximum resulting difference of three percent in the case of helium, the later values resulting in a larger value for w.

6. Comparison with Previous Work

Cloud-chamber measurements of specific probable ionization have been made at the minimum of the ionization curve for both electrons and mesons by Sen Gupta[4] and Hazen.[5] The results of Sen Gupta were obtained with 90 percent argon and 10 percent oxygen in the chamber, but apparently the data have been reduced to the corresponding expected ionization in air or nitrogen so that his results cannot be closely compared with other work. His values of 40 and 37 ion pairs per cm for the minimum ionization of mesons and electrons, respectively, are slightly lower than Hazen's values for air.

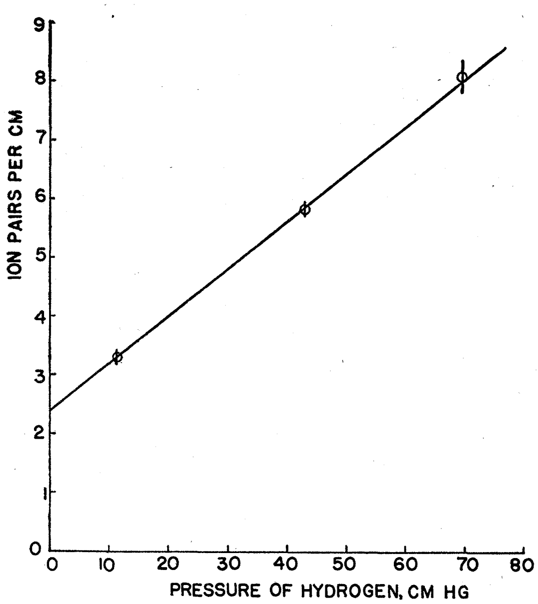

FIG. 6. Specific ionization at minimum of ionization curve in hydrogen and vapor at 14°C.

The discrepancy between the present value of 46 ion pairs per cm in air with Hazen's meson value of 42 is about equal to the sum of the estimated probable errors in the two measurements, but the disagreement with his electron value of 39 is about twice as great. Hazen states that the largest uncertainty in obtaining absolute values from his data is probably in the relatively large resolution correction of about seven percent. His correction of eight percent for ionization in the vapor appears too large by the results of the present work. Hazen's meson and electron values correspond to values of w of 34 and 37 ev, respectively, suggesting that his meson value is the better of the two.

TABLE I. Average energy to produce one ion pair (ev.)

	Air	Hydrogen	Helium	Argon
Older values used for plotting curves	32	36	31	28
Values giving best fit to our experimental results	31.2±1.5	37.2±2.0	26.0±1.6	27.9±1.5
Bakker and Segrè[a]	33.3	35.3	29.9	25.5
Valentine and Curran[b]	35.0	38.0	32.5	27.0

[a] See reference 22.
[b] See reference 23.

Measurements of the specific probable ionization in hydrogen, helium, and argon have been made by Skolil[6] who measured the ionization of cosmic-ray mesons of unknown (in general, higher) energies. His results are shown in Table II together with the ratios of this meson ionization to the values of the minimum electron ionization found in the present work. The probable errors in these ratios are estimated as about eight percent. Hazen has predicted a ratio of 1.18 and has experimentally measured a value 1.12 for air.

An additional value of the average meson ionization in helium has been obtained by Hayward[7] which is in disagreement with these values, 25 percent higher than Skolil's result, corresponding to a ratio of 1.49. The disagreement is in the direction which might be produced by a slight contamination of the helium gas used by Hayward with more heavily ionizing gases.

IV. CONCLUSION

The measured specific probable ionization has been found to vary with velocity as predicted by the Bethe-Bloch theory within the experimental uncertainty for electrons in hydrogen, helium, and air, with ionizations up to six or eight times the minimum ionization, and in argon with ionization up to two and one-half times the minimum. For air, hydrogen, and argon the absolute magnitude of the specific ionization agrees within the statistical probable error of about five percent with the value predicted by the theory using the best directly measured values for the average energy loss per ion pair. For helium the discrepancy is about three times the probable error. However, the magnitude of the specific ionization in helium, as well as that in hydrogen and argon, is in satisfactory agreement with Skolil's measurements of the specific probable ionization of cosmic-ray mesons. The magnitude of the specific ionization in air is ten percent higher than Hazen's

[25] M. Bogaardt and B. Koudijs, Physica 18, 249 (1952); O. Halpern and H. Hall, Phys. Rev. 73, 477 (1948).

TABLE II. Comparison of cloud-chamber results for hydrogen, helium, and argon.[a]

	Average meson ionization (Skolil)	Electron minimum ionization	Ratio
Hydrogen	8.00	6.48	1.23
Helium	9.67	8.13	1.19
Argon	65.5	53.1	1.23

[a] Values are for ion pairs per cm at standard conditions for maximum energy transfer corresponding to formation of 25 ion pairs per primary ionization event.

meson minimum ionization value, the present electron value corresponding to the lower accepted value for w.

These results suggest that the largest uncertainty in careful cloud-chamber measurements of specific probable ionization should be statistical. In measurements on single tracks this statistical uncertainty will, in general, be somewhat high and more serious because of the non-normal distribution of ionization associated with large clusters. The maximum number of drops along a single track is limited by the maximum gas pressure that can be used without resulting in high resolution losses or requiring the use of too diffuse tracks. In the present work the largest number of drops in a single track was about 500, corresponding to a probable error as estimated above of about eight-percent, and with heavier particles considerably longer lengths of such heavily ionizing track may be used.

In order to make absolute measurements it is necessary to be especially careful with respect to the condensation efficiency and in making corrections for the background, drop image resolution, and gas composition. With the light gases a small amount of more heavily ionizing gas may produce an appreciable part of the total ionization, and if the chamber is operated with a saturated vapor, it is necessary to control and measure the temperature accurately if the vapor correction is to be made adequately. For comparative measurements such as those of Hazen and Hayward these sources of systematic error are less important but must still be considered if the operating conditions or density of ionization are not similar for all the tracks used. With such precautions it should be possible to measure the rate of probable energy loss of particles within a few percent from cloud-chamber droplet counts.

We wish to express appreciation to Professor Robert B. Brode for helpful discussions and suggestions.