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Measurement of the Specific Ionization of Fast Mesotrons with an Ionization Chamber and a Linear Amplifier*

W. CRAWFORD DUNLAP, JR.**
Department of Physics, University of California, Berkeley, California
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The ionization of single cosmic-ray particles capable of penetrating 12 cm of lead has been measured with an ionization chamber and a linear amplifier. Measurements made at 14.7 atmospheres with argon indicate an average specific ionization of 71 ion pairs per cm at N.T.P. The results apply on the whole to mesotrons with an energy greater than 2×10^8 ev. The specific ionization of maximum frequency of occurrence is approximately 67 ion pairs per cm in argon. The average value for the ionization obtained with the ionization chamber at 14.7 atmospheres appears to be about 10 percent less than the total ionization. The average value obtained corresponds to the value 48 ion pairs per cm in air at N.T.P. as measured by a method that includes only collisions involving 10^4 ev or less. This result is in good agreement with the cloud-chamber results of Corson and Brode and of Hazen.

I. INTRODUCTION

ALTHOUGH the ionization chamber has been used very extensively for the measurement of ionization *currents* and for the measurement of ionization pulses of large numbers of cosmic-ray particles such as form a shower or burst, the only investigator previous to the present work who has used the instrument for the measurement of the ionization of single cosmic-ray particles is W. F. G. Swann.[1] Swann used a vertical cylinder filled with argon to a few atmospheres pressure. No counter control was used, and all types of pulse were recorded. A rather elaborate analysis had to be made to obtain the probable distribution of path lengths inside the cylinder. In abstract form Swann[2] has also mentioned use of counter control with the ionization chamber.

The work reported in the present paper was begun with the purpose of obtaining a new and independent value for the specific ionization of fast mesotrons, and if possible, of developing a method for obtaining accurately the specific ionization of a single mesotron. The momentum could be measured at the same time by means of a cloud-chamber measurement of the curvature of the track in a magnetic field. Although both the ionization and momentum can be obtained from cloud-chamber photographs, the diffuse tracks needed for accurate droplet counts make determination of the momentum inaccurate if only a single cloud chamber is used.

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** Now at the Western Regional Research Laboratory, Albany, California.
[1] W. F. G. Swann, Phys. Rev. **43**, 961 (1933).
[2] W. F. G. Swann, Phys. Rev. **45**, 258 (1934).

II. APPARATUS

A. General Description

A schematic diagram of the apparatus is shown in Fig. 1. The pulse produced by the motion of

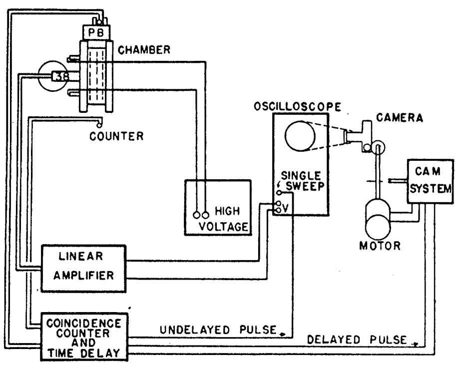

FIG. 1. Schematic diagram of apparatus. The chamber, counters, and 38 tube are mounted inside a shielded box, which is hung by a single piano wire from rubber cushioned supports to minimize microphonic effects.

the ions liberated by the primary mesotron or other particle was detected at the grid of the 38 tube. A high electrostatic field was used to collect the ions. The pulse was pre-amplified by the 38 tube and further amplified by the linear amplifier, which delivered the amplified pulse to the vertical deflection plates of the oscilloscope. The electron beam of the cathode-ray tube was deflected off the screen until a coincidence pulse caused the sweep-circuit thyratron to break down. The thyratron breakdown produced a single trace upon the screen. If the coincidence pulse was accompanied by an ionization pulse, as was ordinarily the case, the pulse appeared upon the screen at the start of the trace. Because of the difficulty of obtaining accurate visual observations of the length of the pulses, and because of the low counting rate—one in ten to twelve minutes—the apparatus was made self-recording and nearly automatic. In the arrangement finally adopted, the traces were photographed by means of a camera equipped with an automatic rewind, actuated by the pulse from the coincidence counter set. A cam system was used to cause the camera gear to be turned the proper fraction of a revolution after each pulse. The apparatus ran automatically for eight or nine hours on one loading of film.

B. The Ionization Chamber

A schematic diagram of the chamber in cross section is shown in Fig. 2. The chamber was cylindrical. The walls were designed to withstand a pressure of at least 70 atmospheres, although for the experiments reported here much lower pressures were used. Three plates were used in order to secure flexibility of operation. Thus, the two outer plates could be connected independently to high voltage sources of the same or opposite sign. In some cases it is desirable to use voltages of opposite sign so that for particles that produce equal ionizations in the two halves of the chamber no net effect is observed at the center electrode. The center collecting plate was insulated by use of amber that was coated with ceresin wax to reduce surface conductivity. The spark plugs used as leads for the high voltage plates were plugged with wax to make them gas-tight. Hard rubber insulators were found to be satisfactory supports for the high voltage plates at voltages up to 7500.

Microphonics arising especially from the vibrations of the plates were a serious problem throughout the course of the work. All three plates were made $\frac{3}{16}''$ thick to minimize these effects, and the whole apparatus was hung by a single piano wire from rubber-cushioned supports. These measures reduced the sensitivity of the system to vibration to the extent that only a very few pulse records had to be discarded because of the presence of microphonic disturbances.

C. The Electrical Circuits

The four-stage linear amplifier was of the negative-feedback type; the feedback was provided by use of un-bypassed cathode resistors and by two feed-back loops. The circuit was built up according to the design of Waddel[3] and differed from that of Waddel in only minor details. The amplification of the amplifier itself, including the 38 tube but not the oscilloscope amplifiers, was approximately 60,000. The calibration of the amplification system is discussed below.

The double-coincidence counter set was of standard design, and will not be described completely. The counter tubes were quenched by

[3] R. Waddel, Rev. Sci. Inst. 10, 311 (1939).

means of the Neher-Harper[4] arrangement, and the coincidences were detected by use of the Rossi[5] coincidence circuit. The resolving time of the counter set was about 2×10^{-4} second. A time delay section employing an 885 thyratron was used to delay closing of the rewind-relay contacts until after the ionization pulse had been photographed. This measure was required because of the relative slowness of the ionization pulse compared to the coincidence pulse and because closing of the relay contacts during recording of the pulse would have caused sufficient sparking to obliterate the trace of the pulse. In order to operate the camera motor from the very short pulse from the coincidence counter, a standard self-holding telephone type relay with two energizing coils was used. The relay was closed by the coincidence pulse and remained closed until the holding current was stopped by the breaking of the relay contacts by the cam on the motor shaft.

The high electrostatic field required for the collection of the ions was obtained by use of a voltage doubler circuit that provided either plus or minus 2900 volts with respect to ground, or both. When it appeared desirable to use even higher voltages, a neon sign transformer was used in the rectifier set, and the circuit was changed so as to provide a single voltage variable from 0 to 7500 volts below ground. No results obtained by use of this voltage, however, are presented here. Since only small currents were drawn from the power supply of the high voltage unit, the little filtering required was provided by two sets of high resistances and one-microfarad condensers. There remained, however, some 60-cycle voltage in the background. This ripple apparently arose from pick-up of atmospheric fields, and was only partially removed by careful grounding of the shielding conductors.

III. CALIBRATION OF THE AMPLIFYING SYSTEM

The over-all amplitude and frequency characteristics of the amplifying system, including the oscilloscope amplifiers, were measured by use of alternating voltages obtained from a signal generator. From the frequency characteristic it was established that the amplification of the system was constant for frequencies corresponding to all collecting times used in the experiments.[6] From the amplitude characteristic it was verified that the length of the pulses was proportional to the voltage produced upon the grid of the 38 tube.

The amplitude and frequency characteristics mentioned above were only relative. The system was calibrated for what might be called the "absolute sensitivity" by use of a polonium alpha-particle source within the ionization chamber. The chief requirements for a good calibration are: (1) The pulses obtained must be of the same order of magnitude as the cosmic-ray pulses studied. (2) If possible, the particles should traverse the chamber in the same way as the cosmic-ray particles are expected to do. (3) The probable error of the result must be made small by observation of a large number of alpha-particle pulses. The method of calibration finally adopted involved use of an alpha-particle gun that confined the beam within a narrow solid angle in a direction parallel to the plates, and close to the voltage plate. The chamber was at a reduced pressure ($\sim$10 mm Hg) and the range of the particles was

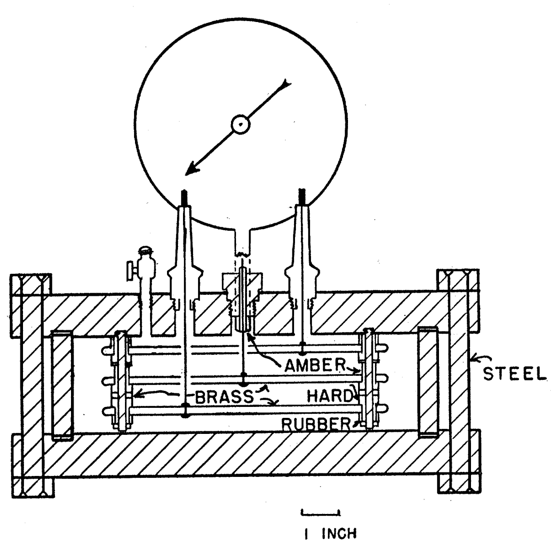

FIG. 2. Schematic cross-section diagram of the ionization chamber.

great enough to enable the alpha-particles to traverse the length of the plates much as a

[4] V. H. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).

[5] B. Rossi, Nature **125**, 636 (1930).

[6] Since these results were obtained with low impedance sources, they do not include an effect to be discussed below, namely, a variation of sensitivity with collecting time caused by the leakage of charge from the grid circuit of the 38 tube.

cosmic-ray particle would have done. By use of the ionization *versus* range data given by Rutherford, Chadwick, and Ellis,[7] the total number of ions expected in the sensitive region was calculated by graphical integration of the ionization. The resulting value of the sensitivity of the amplifying system was 22,300 ions per inch on the screen at the oscillograph gain setting used for the majority of the measurements. The standard deviation for this result is 2.0 percent.

One of the chief difficulties of the experiments was the fact that the time of collection of the ions, for high pressure, was not small compared to the time constant of the grid circuit of the 38 tube. This time constant is effectively the product of the leakage resistance from grid to ground and the capacity of the grid-collector system with respect to ground. The time constant for the apparatus used here was about 0.01 sec. The variation of pulse size with collecting time (or collecting field) was determined by use of the alpha-particle method mentioned above. By comparison of the resulting curve with the saturation curve for alpha-particles given in Jaffe's paper on columnar ionization,[8] it was found that in order to have the uncertainty caused by the collecting time effect less than 10 percent, the collecting time must be less than 0.005 sec. The collecting time must be less than 0.003 sec. for an uncertainty less than 5 percent. In addition, each value obtained at 27 atmospheres was increased by 25 percent, at 21.5 atmospheres by 12 percent, and at 14.7 atmospheres by 5 percent, to correct for loss of pulse size from the collecting time effect. The values for the collecting time used above were determined for the present calculations by use of the value 1.7 cm^2/volt sec. for the mobility of argon containing slight impurities of oxygen.[9] (Argon of 96 percent purity was used in this work.)

IV. SOME FURTHER CONSIDERATIONS AND ASSUMPTIONS

In the calculation of the specific ionization of the penetrating particles from the observed pulse sizes, the following assumptions were made: (1) Recombination can be neglected. Clay[10] has shown that for air in a shielded ionization chamber, with fields of the order of 2000 volts/cm and pressures of 15 to 25 atmospheres, the lack of saturation is only one or two percent. Since the pressures used in this work varied from 14.7 to 27 atmospheres, and the collecting field for most of the measurements was 1900 volts/cm, recombination can reasonably be neglected as a source of error. (2) The measured ionization is proportional to the pressure. Clay[11] has shown that the measured ionization in argon is proportional to the pressure, to within a few percent up to 60 atmospheres.

The path length used in the calculation of the probable values of the specific ionization is 17.0 cm. This length is not exactly that of the plates, but is a corrected value slightly greater than the length, 15.9 cm. The corrections take into account the effect of the fringing fields at the ends of the plates and also the fact that the Geiger counters subtended an appreciable solid angle. The counters were disposed so as to cover the entire region between two of the plates.

By use of the alpha-particle calibration and the above value of the probable path length, the "probable value of the specific ionization" was calculated, and it is equal to the observed ionization (corrected for collecting time effect) divided by the path length and by the pressure in atmospheres, reduced to standard conditions.

The expression "probable value of the specific ionization" should be used to denote the results, since it is not certain that a given pulse was produced by a single particle nor that the particle, assuming it to be single, traversed the chamber in the expected way. On the whole, however, the results can be ascribed to the action of single penetrating particles, presumably mesotrons. Starr[12] and others[13] have shown that the great majority, of the order of 90 percent, of double coincidences obtained with a few centimeters of lead between the counters is caused by single penetrating particles that do not produce showers. In the present experiments, the walls of the

[7] Rutherford, Chadwick, and Ellis, *Radiations from Radioactive Substances* (Cambridge University Press, 1930), p. 80.
[8] G. Jaffe, Ann. d. Physik **47**, 303 (1913).
[9] L. B. Loeb, *Kinetic Theory of Gases* (McGraw-Hill Book Company, Inc., New York, 1934), p. 619.

[10] J. Clay and K. Oosthuizen, Physica **4**, 527 (1937).
[11] J. Clay and M. Kweiser, Physica **5**, 725 (1938).
[12] M. Starr, Phys. Rev. **53**, 6 (1938).
[13] S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **51**, 884 (1937).

chamber, the block of lead, and the concrete roof above the apparatus are equivalent as far as ionization loss is concerned, to about 12 cm of lead. Using the Bethe-Bloch value of 1.5×10^6 ev cm^2/g, for the ionization loss of a fast mesotron at the minimum of the ionization *versus* energy curve, we see that the results apply on the whole to mesotrons with energies above 2×10^8 ev.

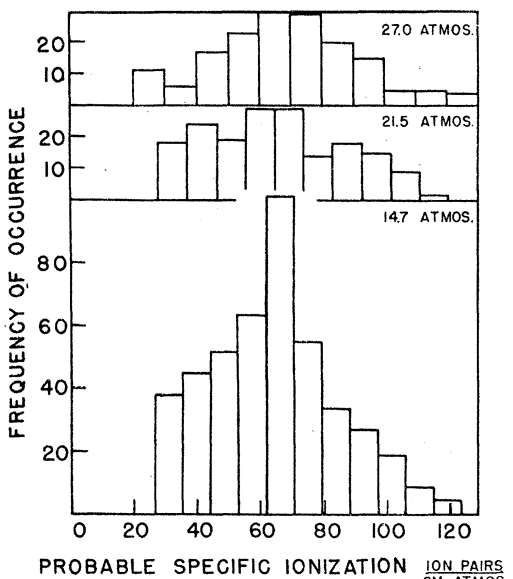

FIG. 3. Pulse-size-frequency distributions, plotted as block diagrams. The abscissa is the "probable specific ionization," that is, the specific ionization to be ascribed to the pulse assuming it to be produced by a single particle that traverses the chamber with path length 17.0 cm.

V. RESULTS AND DISCUSSION

Measurements were made at pressures of 27.0, 21.5, and 14.7 atmospheres of argon. Higher pressures were not used because of the limitations on the collecting time mentioned in Section III. About 1000 pulses were obtained in the form of photographic records, of which 700 were suitable for measurement. The block diagrams of Fig. 3 show the frequency of occurrence of certain specific ionization intervals of widths indicated. From the study previously mentioned of the variation of sensitivity of the amplifying system with time of collection, it was found that at 22 atmospheres there was an uncertainty of 20 percent in each individual result, 10 percent at 21.5 atmospheres, and about 5 percent at 14.7 atmospheres. In spite of this uncertainty, and of the previously mentioned corrections to the ionization values at the three pressures used, the maxima of the three distributions all appear to be in the same region. There is of course a pronounced broadening of the distributions at the higher pressures, which can be attributed to the collecting time effect.

The frequency distribution curve is considerably broader than would be expected if single particles having an energy spectrum such as that found by Blackett and obeying the Bethe-Bloch ionization law were passing through the chamber in the directions defined by the two Geiger-Müller counters.[14] In particular, it is to be noticed that there is a considerable number of pulses smaller than that most frequently occurring, as well as a large group of pulses longer than that most frequently occurring.

This broadening cannot be attributed to the "collecting-time effect," since the error in each result introduced by this effect at 14.7 atmospheres is only about 5 percent. There are, however, additional factors peculiar to the experimental method that may be responsible for the observed breadth of the curve. Some of these are: (1) Single penetrating particles may pass through the counters without traversing the full length of the sensitive region of the chamber to produce a small pulse. The coincidence pulse would most likely be produced in this case by scattering of the particle in the walls of the chamber or by production of a knock-on electron at the outer edge of the chamber. (2) Showers may trip the counters and one or more of the particles of the shower may pass obliquely through the sensitive region of the chamber to produce a small pulse. (3) Accidental coincidences may be caused by two independent cosmic-ray particles, one of which by chance may also pass obliquely through the sensitive region of the chamber to produce a small pulse. It is expected that showers are mainly responsible for the existence of both the very small pulses and the very large pulses observed.

The value taken for the specific ionization of maximum occurrence is 67 ion pairs per cm in argon at N.T.P. The *average* specific ionization is

[14] For information on the question of the constancy of specific ionization of cosmic ray particles with energy, see W. E. Hazen, Phys. Rev. **65**, 259 (1944).

also of interest. Using only the 14.7-atmosphere results we find by counting squares that the average specific ionization is 71 ion pairs per cm.

In order to obtain maximum accuracy in measurement of the most frequently occurring pulses, pulses with lengths more than about three times that most frequently occurring extended beyond the limits of the oscilloscope screen and were not measurable. By use of minor modifications of the photographic technique, the range of investigation can be modified so as to include any range of ionization, from that of single particles to that of importance in the study of showers and bursts.

If one uses Hopfield's assumption[15] that the ionization is proportional to the number of extranuclear electrons, then the specific ionization for air should be about 14.5/18 that for argon. For the average specific ionization in air from the results at 14.7 atmospheres, one obtains a value of approximately 60 ion pairs per cm.

Although a minimum pressure of 14.7 atmospheres was used in the chamber, it cannot be assumed that the average ionization obtained in this work represents the total ionization.[16] A secondary produced in the gas can impart only a limited energy to ionization and excitation within the sensitive region of the chamber. Assuming a constant ionization of 60 ion pairs per cm, and an average energy of 25 ev in argon for production of one ion pair,[17] we find the maximum energy of dissipation of a secondary to be 3.75×10^5 ev, if we assume that the secondary passes through the sensitive region in a straight line with path length 17.0 cm. This assumption is doubtful, however, since scattering of the particle would have the effect on the whole of shortening the path length by deflecting the particle into one of the plates. Secondaries with energies above 375 kev will be able to contribute only this same energy. Thus although it is rather difficult to calculate a precise upper limit to the secondary energies that are detected, for a rough calculation we take 375 kev as an effective upper limit and consider that secondaries with energies up to 375 kev are completely detected, and that secondaries with energies above 375 kev are completely undetected.

The total collision loss $\hat{\epsilon}_t$ in air is given by Rossi and Greisen[18] from the Bethe-Bloch theory to be 1.8×10^6 ev cm^2/g in air. At one atmosphere the total average energy loss is 2300 ev/cm. Rossi and Greisen also show that the average energy loss when only collisions up to 10^4 ev are considered is 28.5 percent less than the total, or $\hat{\epsilon}_{10^4}=1700$ ev/cm. We now wish to add to the latter figure the energy loss caused by collisions to secondaries between 10^4 and 3.75×10^5 ev. The probability of production of a secondary electron of energy E by a fast mesotron of high energy is given fairly accurately for air by the Rutherford formula[19]

$$\chi(E)dE=\frac{98dE}{E^2}\frac{\text{ev}}{\text{cm}}.$$

The average energy loss $\hat{\epsilon}_{E_1}^{E_2}$ caused by all such secondary electrons in the range E_1 to E_2 is

$$\hat{\epsilon}_{E_1}^{E_2}=\int_{E_1}^{E_2}E\chi(E)dE=98\int_{E_1}^{E_2}\frac{dE}{E}.$$

For $E_1=10^4$ ev, $E_2=3.75\times 10^5$ ev,

$$\hat{\epsilon}_{10^4}^{3\times 10^5}=98\ln 37.5\backsimeq 360 \text{ ev/cm}.$$

Since the ionization chamber effectively measures $\hat{\epsilon}_{10^4}+\hat{\epsilon}_{10^4}^{3.75\times 10^5}$, we find a fraction 2060/2300 =90 percent for the fraction of the total collision loss measured by the ionization chamber as used in the present work. Since the cloud-chamber result (for energies less than 10^4 ev) is 28 percent below the total ionization, the cloud-chamber result is about 20 percent less than the ionization chamber result. Thus for comparison of the present ionization chamber results with the cloud-chamber results, we should use the value $60-(0.2\times 60)=48$ ions pairs per cm path in air at N.T.P.

Corson and Brode[20] found a minimum ionization of fast electrons in air of about 50 ion pairs per cm. Bagley[21] found an average ionization of

[15] J. J. Hopfield, Phys. Rev. **43**, 675 (1933).
[16] I am indebted to Dr. Wayne E. Hazen for pointing this out to me and for valuable assistance in connection with the point.
[17] See reference 7, p. 81.
[18] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).
[19] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 243 (1941). See also reference 14.
[20] D. Corson and R. B. Brode, Phys. Rev. **53**, 773 (1938).
[21] D. G. Bagley, Ph.D. Thesis, University of California (1941).

cosmic-ray particles in nitrogen of 43 ion pairs per cm. Hazen[22] has recently obtained a value of 50 ion pairs per cm for the average specific ionization in air of a large number of tracks of penetrating rays obtained at sea level and 100 feet underground.

It is of interest to compare the present results with those obtained by other workers using ionization chamber methods. Swann[23] obtained a value of 50 ion pairs per cm in argon by use of the uncontrolled ionization chamber having a thin wall and with little shielding around the chamber. Stuhlinger[24] in work with a proportional counter at one-half atmosphere, found a value for the specific ionization of the hard component in air of 35 ion pairs per cm.[25] Stuhlinger in this same work, and Swann[26] in work reported only in abstract form, have found a second maximum in the ionization curve. Indeed Stuhlinger gives a curve showing six or eight fairly well-defined maxima which he ascribes to various combinations of primary hard particles and softer secondary particles. The primaries are assumed from the position of the first maximum to have a specific ionization of about 35, and the secondaries then are found to have an ionization of about 50 ion pairs per cm, referred to air.

There is some evidence of such a second maximum in the 21.5-atmosphere results, but none in either the 27-atmosphere nor in the 14.7-atmosphere results. Since the low pressure results are the most reliable, it must be concluded that the present results indicate that there is only one maximum in the frequency distribution.

VI. CONCLUSION

The results obtained in this paper for the average value and for the most frequently occurring value of the specific ionization obtained under the described conditions are considered to be accurate to within eight or ten percent. The principal sources of error in these quantities are (1) the error of calibration of the sensitivity of the amplifying system, and (2) the fact that the pulses were classified into only a relatively few large groups. This classification was dependent upon the diffuseness of the trace, which in turn was determined by the background disturbances in the 38 tube.

In evaluating the question of the accuracy with which a *single* particle can be measured, we are probably upon safer ground if we examine the breadth of the experimental curve of Fig. 3 than if we rely upon estimates of the uncertainties that may be supposed to be introduced into each measurement. The curve has a half-breadth which appears to be some 25 or 30 percent of the most frequently occurring value. Although there is no reason to suppose that such a large error as 25 percent was inherent in the method of measurement of the ionization in the chamber, nevertheless, the presence of knock-on electrons from the walls or of pulses due to showers leads to essentially the same effect. Although use of the chamber in conjunction with a cloud chamber might remove the uncertainty as to whether a given pulse is associated with an air shower, there appears to be no way of being sure that a knock-on electron is not produced in the wall of the chamber to give a misleading impression of the specific ionization of the particle. Thus the usefulness of the method outlined in the present paper is greatest for work in which the most frequently occurring value, based upon as large a number of pulses as possible, can be used as the measure of the ionization.

VII. ACKNOWLEDGMENT

The present work was suggested by Professor R. B. Brode, to whom the author is also indebted for helpful suggestions and discussions, especially during the early phases of the investigation.

[22] W. E. Hazen, Phys. Rev. **65**, 259 (1944).
[23] W. F. G. Swann, Phys. Rev. **43**, 961 (1933). See also footnote, T. H. Johnson, Rev. Mod. Phys. **10**, 211 (1938).
[24] E. Stuhlinger, Zeits. f. Physik **108**, 444 (1942).
[25] Information has just been received of the publication of a paper "On the use of the linear amplifier for the measurement of the ionization of single particles" by S. A. Wytzes and G. J. van der Maas, Physica **10**, 419 (1943). No details, however, are available at the present writing.
[26] W. F. G. Swann, Phys. Rev. **61**, 393 (1942).