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The Average Specific Ionization of Cosmic-Ray Mesons in Hydrogen, Helium, and Argon

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Counter-controlled, cloud-chamber photographs have been taken of cosmic-ray meson tracks in hydrogen, helium, and argon gases. The chamber was operated in such a way that the average probable ionization could be determined from the counted number of drops that condensed on positive ions. Clusters of droplets that required energy transfers up to 25×(average energy spent per ion pair) were included. The observed results were corrected for the ionization in the alcohol and water vapors used in the chamber. The ionization correction amounted to less than 25 percent for hydrogen and helium gases and less than one percent for argon gas. The average probable ionization per cm at N. T. P. in hydrogen gas was 8.00, in helium gas 9.67, and in argon gas 65.5. The probable error was about seven percent. The results were used to check with theory. There was very good agreement between theory and experiment for hydrogen, argon, and air, but in the case of helium the discrepancy exceeded the estimated experimental error.

INTRODUCTION

THE term, "specific ionization," is applied in a general way to any quantity that represents the number of ion pairs per centimeter of track length. The various methods used in measuring the specific ionization of cosmic-ray particles in gases and the advantages and disadvantages of these methods have been discussed by Johnson,[1] Brode,[2] Hazen,[3] and others.

In the determination by the ionization-chamber method, the ionization is given by an expression essentially of the form $I=N/JL$, where N is the total number of ions per sec. per cm^3 as measured by the ionization chamber, J is the number of particles traversing unit volume per sec., as measured by a counter, and L is the average track length. Since these data are independently collected, there is uncertainty in the interpretation of the results thus obtained.

Using the pulse-ionization-chamber method, one observes the number of ions collected when a single particle passes through the ionization chamber. Since each track will traverse a different path length in the ionization chamber, allowance must be made for the shape of the chamber. Dunlap[4] overcame this limitation by using a counter-controlled, pulse-ionization chamber. In this way the track was confined in direction to the solid angle subtended by the counters and in length to the vertical length of the plates of the chamber.

A cosmic-ray meson in passing through matter produces secondary electrons ejected from molecules. These secondary electrons have sufficient energy, on the average, to produce additional ions. The path of the secondary electrons is usually so short that nearly all the ions lie close together in a group.

If the expansion of the cloud chamber in the determination of the ionization by the cloud-chamber method is performed immediately after the passage of the meson, either a single globule of liquid is formed on the entire group of ions or the individual droplets formed on each ion are so close together that they are not resolved and thus appear as a single globule of liquid. A count of globules per cm of track length gives a measure of the *primary* ionization. If the expansion of the cloud chamber is delayed a few hundredths of a second after the passage of a cosmic-ray meson, the ions will have spread by diffusion so that after expansion each ion will be the nucleus of a drop of liquid, provided the expansion was great enough. An electrical clearing field from the front to the rear of the chamber separates the positive and negative ion-droplets into separate columns. The droplets in these columns, if photographed under favorable conditions, can in most cases be resolved and counted. Occa-

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[2] R. B. Brode, Rev. Mod. Phys. **11**, 222 (1939).
[3] W. E. Hazen, Phys. Rev. **65**, 259 (1944); **67**, 269 (1945).
[4] W. C. Dunlap, Jr., Phys. Rev. **67**, 67 (1945).

sionally a secondary electron of exceptionally high energy makes a branch track. If the branch track is short, it is referred to as a cluster. If the ions along all of the branch tracks as well as the ions in the clusters are included, the results thus obtained would give a measure of the total ionization. However, when one uses a cloud chamber at pressures suitable for counting drops, it is not possible to have all the branch tracks within the cloud chamber. With large ionization chambers operated at high pressures the observed results represent nearly the *total* ionization. Finally, the *probable* ionization is defined as the average ionization exclusive of the ions in clusters greater than a certain upper limit.

Cloud-chamber measurements of cosmic-ray ionization in air have been made by Corson and Brode.[5] Using the cloud-chamber method, Hazen[3] has made extensive observation of the average specific ionization of mesons in air at sea level and down to 400 feet underground. The purpose of the present work was to make cloud-chamber measurements of the average probable specific ionization of cosmic-ray mesons in hydrogen, helium, and argon gases.

Cosmic-ray mesons were chosen for this study because they are rather good mono-ionizing particles. This fact may be seen readily from a study of the energy distribution curve and the theoretical ionization curve for mesons. According to theory, the ionization produced by a high speed particle should decrease to a minimum value rather rapidly as the speed of the particle increases up to approximately 95 percent of the velocity of light. This decrease in ionization is caused by the decrease in the time during which the meson can act on the atom. At higher speeds the probable ionization should increase very slowly, approximately as the logarithm of the energy. This increase in ionization is caused by the increase in sharpness of the pulse resulting from the contraction of the electric field in a plane perpendicular to the motion of the particle. It is in this latter region of the energy spectrum, where the ionization is increasing logarithmically, that most of the cosmic-ray mesons occur. Experimental evidence, however, leads to a power law distribution.[6] Thus at the higher energy end of the spectrum we may expect less than 20 percent of the mesons to have an ionization 20 percent greater than the ionization at the maximum of the distribution. At the lower energy end of the spectrum there are few mesons with energies less than 2×10^8 ev, the energy at minimum ionization. In the energy range 1.8×10^8 to 1.5×10^7 ev, Greisen[7] points out that we may expect only eight percent of all mesons. According to Williams,[8] we may expect about four slow mesons out of 10,000 cosmic-ray particles, i.e., mesons with ionization 2.5 times the ionization minimum. Thus we may expect no large variation in the probable ionization of the individual cosmic-ray mesons.

EXPERIMENTAL PROCEDURE

Photographs were taken of diffuse, counter-controlled meson tracks in a cylindrical cloud chamber 30 cm in diameter and 10 cm deep. The front clearing-field electrode consisted of a ring with very thin nickel wires stretched horizontally across the ring three centimeters apart. This electrode was placed immediately behind the front glass and charged to 250 volts, positive with respect to the back of the chamber. The wires were so small and so far out of focus that they did not interfere with the photographing of the drops. From the evidence of the uniformity in separation of the ion columns in a track, we could judge that the clearing field was quite uniform in the region in which tracks were photographed and probably did not give rise to any distortion in the length of the track.

Studies of condensation efficiencies[9] for liquid mixtures[10] of ethyl alcohol and water (70 percent ethyl alcohol) indicate that if 20 percent of the negative-ion drops are present, nearly all of the positive ions are represented by drops. This negative-ion criterion does not change rapidly for ethyl alcohol mixtures from 70 percent down to 40 percent. With mixtures below 40 percent ethyl alcohol, the percentage of nega-

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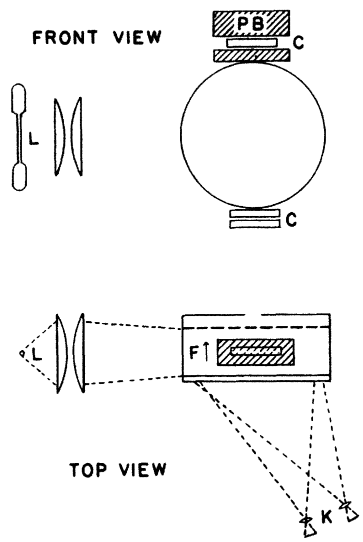

FIG. 1. Schematic diagram showing the cloud chamber and the relative positions of the counters (C), lead (Pb), light source (L), and cameras (K). The clearing field is indicated by F. The light beam through the chamber was made somewhat convergent in order not to illuminate the front glass and to provide nearly constant exposure for tracks on opposite edges of the chamber.

tive-ion drops must be higher than 20 percent in order that one may be quite certain that most of the positive ions are represented by drops. A 50 percent negative-ion criterion was used in this work.

The chamber was evacuated and then filled with the gas and with more than enough of a liquid mixture of ethyl alcohol and water, containing 80 percent ethyl alcohol, to saturate the chamber. The chamber was operated with pools of liquid mixture on the bottom. No trouble was encountered because of electrolysis even with clearing-field electrolysis currents as high as 50 microamperes. During the time required for the performance of the experiment, about three days for each gas, some of the alcohol diffused out through the rubber diaphragm. Therefore the 50 percent criterion was chosen. In most of the tracks the positive and negative ion columns appeared to be equally dense, indicating that the condensation efficiency was certainly nearly 100 percent for positive ions.

Turbulence was avoided by maintaining the room and chamber at as near a constant temperature as possible. None of the observed tracks within the illuminated region of the chamber was noticeably distorted.

The cloud chamber was controlled by a three-counter telescope. Two of the counters were placed below the chamber. The counters were quenched by Neher-Harper quenching circuits, which were coupled to a conventional Rossi coincidence circuit. The tubes used in the above circuits were the triple-grid type 77 except for the trigger tube, which was an 884. With three counters in the telescope more than 99 percent of the pictures yielded visible counter-controlled tracks.

In order to distinguish between electron and meson tracks, a lead block of 10-cm thickness was placed above the top counter. It was very unlikely that an electron could penetrate this lead without producing an electron shower. Photographs with two or more simultaneously occurring tracks were not used. Since additional lead was placed just over the chamber and under the top counter, it was very likely that, out of the few instances where knock-on electrons accompanied the mesons from the lead, both the meson and the electron would be seen.

Two 35-mm Retina cameras with 50-mm lenses were rebuilt to have adjustable tilting of the image plane. This was necessary in order to obtain sharp focus for tracks lying within the volume defined by the counters. The scattering angles for the light that entered the cameras were 60° and 73°, and the corresponding lens apertures that gave satisfactory drop images were f:16 and f:12, respectively. The photographs were taken on Agfa Ultra Speed film. Since grain was not of great importance in studying the number of drop images and since the greatest possible contrast was desired, the films were developed in DK50 for about twice the normal development time.

The cameras were opened at the time of expansion, but a time-delay circuit employing an 885 thyratron was used to delay the flashing of the lights. During the time between the expansion and the flash, the drops grew to a size such that they scattered enough light to be photographed. The cameras were coupled mechanically, and the film was rewound by an electric motor.

The cloud chamber was illuminated by an argon flash tube similar to that described by Hazen.[3] A 450-mf condenser bank at a potential

TABLE I. Ionization by cosmic-ray mesons in gases.

	Hydrogen	Helium	Argon	Air
Observed ionization N.T.P.	11.5	12.6	63.5	
Root-mean-square deviation	0.10	0.11	0.12	
Corrected ionization to dry gas N.T.P.	8.00	9.67	65.5	51
Ratio of ionization to ionization in air	0.160	0.194	1.33	1.0
Ratio of ionization to electron density	4.00	4.84	3.68	3.5
Calculated values of C	0.166	0.215	0.170	0.17
Primary ionization N.T.P.	5.5	6.5	29	21

of 1000 volts was discharged through the flash tube. Crosswise illumination was used, as shown in Fig. 1, in order not to illuminate the front glass or the front clearing-field electrode. As an aid in the focusing of the light source, the region to be illuminated was marked out on the opposite side of the cylinder. A phosphorescent screen was placed over the marked-out region. A flash of the tube produced a phosphorescent glow that lasted long enough for visual observation, thus indicating what adjustments of the light source were necessary.

The drop images were counted on the film with the aid of a microscope that was equipped with a micrometer-motion stage. In some cases both films were counted as a check, particularly when the drop images on one film appeared to be slightly enlarged due to overexposure.

Scratch marks were made on the film to indicate the portion of the track that satisfied the 50 percent negative-ion criterion discussed above. Portions of the track that were crossed by stray tracks were also marked and then omitted.

Secondary rays produced dense clusters of drops which could be counted in most cases. As an aid in obtaining the number of drops in a dense cluster in the positive-ion column, the same cluster was counted in the less dense negative-ion column, and the result was multiplied by the ratio of the plus to minus drops in corresponding adjacent lengths of the track. Clusters were excluded that exceeded the average number of drops for that length of track by more than 25 drops. It was, however, seldom necessary to exclude clusters. Hazen[3] has found that statistical variations from one track to the next were greatly reduced by the exclusion of large clusters.

In order to determine the length of a counted section of track, the films were replaced in the cameras where they were held in their original lateral and axial positions by lateral and back-plate springs. The images were reprojected onto a screen through a glass equal in thickness to that through which the photographs were taken and placed at the same angle. The actual projected lengths of the tracks that satisfied the 50 percent negative-ion criterion were measured. The reprojection distance was checked against the original distance between the cameras and the cloud chamber. The reprojection was done with such care that drop images could be made to coincide along the entire track length.

EXPERIMENTAL RESULTS AND DISCUSSION

The total pressure in the chamber for the hydrogen and helium experiments was 152 cm of Hg in each case; for the argon experiment the total pressure was 100 cm of Hg. The observed number of drops per cm of track length was reduced to N.T.P., and corrections were made for the ionization of the alcohol and water vapor mixture. The ionization of the vapor and gas mixture may be given by an expression of the form:

$$I = p_1 I_{\text{gas}} + p_2 I_{\text{H}_2} + (p_2 + p_3) I_{\text{O}} + p_3 I_{\text{C}_2} + p_3 I_{\text{H}_6}, \quad (1)$$

where I represents the observed number of drops per cm of track length; p_1 represents the partial pressure of the gas, and p_2 and p_3 the partial pressures of the water vapor and alcohol vapor respectively. The values, I_{H_2}, I_{H_6}, I_{O}, and I_{C_2}, were approximated by assuming that the ionization due to these molecules was proportional to their respective electron densities. For example, in making the correction for helium gas, I_{H_2} equals $2/2 \times I_{\text{He}}$; $I_{\text{H}_6} = 3 \times I_{\text{He}}$; $I_{\text{O}} = 8/2 \times I_{\text{He}}$; and $I_{\text{C}_2} = 12/2 \times I_{\text{He}}$. The correction in the case of hydrogen and helium gases was less than 25 percent; for argon the correction was less than one percent.

The corrected values as found in these experiments for the average specific ionization of 25 or more meson tracks in each of the gases are shown in Table I. Energy transfers greater than η were excluded (η to be explained later).

The observed value shown in Table I for the ionization in argon must be corrected for the overlapping of drop images. Two drop images may be resolved if the overlap is equal to or less than the radius of the drop. The diameter of a correctly exposed and sharply focused drop image was approximately 0.02 mm. The diameter of the drop in the chamber, however, was not equal to the magnification, M, times the image diameter. The track widths measured on the film varied from 0.25 mm to 0.40 mm. In the chamber the drop columns would be M times as wide. The average value of M was 6.1. The correction for the ionization in argon gas amounted to about 4 percent, which should be added to the observed value shown in Table I, i.e., $63.0+0.04(63.0)=65.5$. This correction is a minimum because it was determined on the basis of a random distribution of drops in the track. For hydrogen and helium gases the correction was less than one percent.

The number of drops counted in a track length in helium and hydrogen gases was between 300 and 400 and in argon gas between 400 and 1000. The statistical variation in the ionization of an individual track is determined by the number of primary ionization events. The primary ionization in helium gas is 6.5 primary ion pairs per cm,[11] which gives a ratio of probable to primary ionization of 9.67/6.5 or about 1.5. In the case of hydrogen, this ratio of probable to primary[12] ionization is 8.00/5.5 or about 1.5. The probable statistical deviation is:

$$0.67\frac{(200)^{\frac{1}{2}}}{200}\sim 0.05.$$

The probable error as estimated on the basis of least count and experimental uncertainties is less than five percent.

Block diagrams of the distributions for each of the gases are given in Fig. 2. No slow mesons were observed. The root-mean-square deviation was 11 percent. If these data conform to a normal distribution, then the corresponding most probable error would be 0.67×11 percent or about seven percent. Thus from the experimentally observed spread it is apparent that the mesons were essentially mono-ionizing.

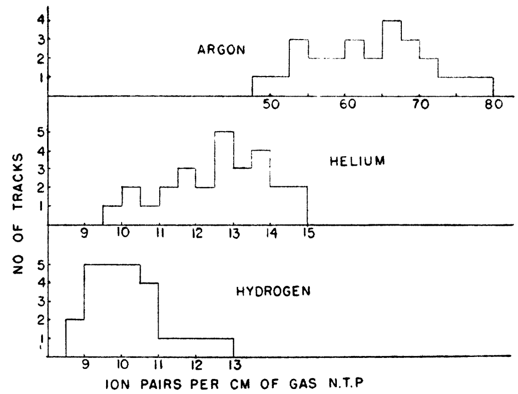

FIG. 2. Block diagram showing frequency distribution of the probable ionization of cosmic-ray mesons in hydrogen, helium, and argon gases. The mean value of the ionization was 11.5 in hydrogen, 12.6 in helium, and 65.5 in argon. The root-mean-square deviation was about 11 percent.

The results of these experiments can be used to check the theory. The energy loss by collision can be given by a theoretical expression[13] of the form:

$$k_\eta(E)=\frac{2C\mu Z}{\beta^2 A}\left(\log\frac{2\mu\eta}{I^2(Z)}\frac{\beta^2}{(1-\beta^2)}-\beta^2\right), \quad (2)$$

where k_η is the energy loss per g/cm^2 by collision with electrons and where the maximum energy transferred is less than η. This last symbol represents $25\times V_0$ where V_0 is the average energy[14] spent per ion pair. $\mu=mc^2=$ rest energy of an electron. $I(Z)$ represents a mean energy of excitation of an atom of atomic number Z. According to Bloch's[15] theory of excitation energies, the mean excitation energy for atoms containing many electrons is proportional to the atomic number Z. The most reliable measurement of the constant of proportionality available is $I(Z)=11.5Z$, as determined by Wilson[16] from observations of stopping power. For a hydrogen-like atom Bethe[17] gives $I(Z)=1.1\times J$, where J is

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[16] R. R. Wilson, Phys. Rev. **60**, 749 (1941).
[17] H. A. Bethe, Ann. d. Physik **5**, 325 (1930).

the observed ionization potential. Using this expression for H_2, we have $I(Z)=1.1\times 15.9=17.5$. Williams[18] using Wheeler's[19] data for the "stopping power" of helium calculates a value of 44 volts for the mean excitation energy for helium gas. In view of the small spread in the ionization of the individual mesons, it appears that a reasonable effective value of $\gamma^2=1/(1-\beta^2)$ could be taken near the minimum of the theoretical ionization curve, i.e., $\gamma^2=20$, $\beta=0.975$. Fortunately, the value of C calculated with the use of Eq. (2) is not very sensitive to changes in the values of γ^2 or $I(Z)$ since these quantities occur inside the log term. A change of γ^2 by a factor of 10, for instance, affects the value of C by only 7/166 or about 4.5 percent. It is, therefore, not important to know the exact value of γ^2.

The values of C calculated from Eq. (2) for hydrogen and argon gases agree exceptionally well. A value of 0.17 for C is obtained with the use of Hazen's[3] value of 51 ion pairs per cm for the average specific ionization in air and with $I(Z)=11.5\times 7.23$, and $A=14.78$. No completely satisfactory explanation has been found for the discrepancy in the case of helium; otherwise there is satisfactory agreement between theory and experiment. Williams[20] suggests the possibility that the experimental value of the energy per ion pair is too low for helium gas. But larger values of V_0 only increase the value of C and, likewise, the discrepancy.

There is another possible explanation for the large value of C. Helium gas has a metastable state of energy corresponding to 19.77 volts. A meson may excite this metastable state. There are some secondary electrons along the meson track that possess insufficient energy to ionize a helium atom but sufficient energy to excite this metastable state. A helium atom thus excited could in turn ionize a vapor molecule by collision with it. This ionization of vapor molecules seems possible since the ionization potential of water is approximately half that of helium. The additional vapor ions thus formed would serve as condensation nuclei for droplets along the track. These droplets would be counted and would tend to increase the observed ionization for the gas and, likewise, the calculated value of C. But this effect is probably not large enough to account for the discrepancy that exists. The ionization potential of helium gas is 24.5 volts, while the average energy spent per ion pair is 27.8 volts. This small difference would indicate that very little energy is lost in helium in excitation.

It is of interest to compare the results of the present work on argon with those obtained by others. Using a counter-controlled ionization chamber under 12 cm of lead, Dunlap[4] obtained a value of 71 ion pairs per cm for the average specific ionization in argon. Energy loss to secondaries by collision are included up to $\eta=3.75\times 10^6$ ev. This result represents about 90 percent of the total ionization. Where η is 800 ev, the cloud-chamber method measures about 66 percent of the total ionization. Thus, $(71\times 100)/90-0.34\times 71=55\pm 10$ percent is the calculated value expected as compared to the value 65.5 ± 5 percent observed in the present work. This difference is just within the limits of the probable errors of the experiments.

Clay and Oosthuizen,[21] using an uncontrolled ionization chamber shielded with 12.5 cm of iron, obtained a value of 1.65 for the ratio of the ionization in argon to the ionization in air for all cosmic-ray particles. The results in the present work indicate a corresponding ratio of 65.5/51 or about 1.3.

ACKNOWLEDGMENT

The author is deeply indebted to Professor Wayne E. Hazen, who suggested the problem, for his continued interest, suggestions, and helpful discussions.

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