holes which were caused by a discharge constantly changing its position of the point because of alterations of the oxide-coated surface film by the impact of positive ions.

The introduction of impurities made the investigations difficult because it immediately reduced the currents by a factor of more than one hundred, thus making the time of observation prohibitively long. There was no doubt, however, that etching also occurred in these cases.

While not many data as to the mechanism are at hand, the character of the process is sufficiently like the sputtering phenomenon in glow discharges to make one feel that one is here dealing with a type of sputtering occurring at relatively low positive ion energies, but in distinction to sputtering caused by positive ions of high energies in low pressure glow discharges, this sputtering occurs with low ion energies at high current densities.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Professor Leonard B. Loeb, who suggested the problem, guided its progress, and helped in the interpretation of the observed data. The writer is also indebted to the Research Corporation of New York, under whose Research Fellowship Grant at the University of California the main part of this work has been completed.

PHYSICAL REVIEW VOLUME 63, NUMBERS 3 AND 4 FEBRUARY 1 AND 15, 1943

The Specific Primary Ionization of Cosmic Rays in Helium

WAYNE E. HAZEN
University of California, Berkeley, California
(Received November 17, 1942)

Values for the specific primary ionization of 46 cosmic rays in helium have been determined from cloud-chamber photographs. A magnetic field allowed separation into two groups: 21 electrons with energies near the energy for minimum ionization had a mean ionization of 7.33 ± 0.12 per cm, and 26 mesotrons with energies greater than the energy for minimum ionization had a mean ionization of 7.23 ± 0.12 per cm. The expected value for the latter figure, taking into account a logarithmic rise of ionization with energy, is 8.80 ions/cm. The experimental value for the minimum specific primary ionization in helium (corrected for the ionization in the vapor) is 6.5 ± 0.1 at N.T.P. Three protons were observed in the $H\rho$ range in which they can easily be identified; in this $H\rho$ range three particles constituted approximately one percent of the radiation.

THE primary ionization of electrons from radioactive sources has been determined by Williams and Terroux[1] in hydrogen and oxygen and by Skramstad and Loughridge[2] in nitrogen and neon. C. T. R. Wilson[3] counted the primary ions along the tracks of electrons with energies between ten and thirty kev. Theory predicts a logarithmic increase in ionization with energy when the kinetic energy is large compared to the rest energy. Kunze[4] failed to detect any rise in ionization in measurements on ten cosmic-ray particles with energies around 10^9 ev. Since it is now known that most of the particles with this energy are mesotrons, the ionization should correspond to that of electrons with $H\rho=10^9m/300\mu$, where μ and m are the masses of the mesotron and the electron, respectively. When this correction is made, Kunze's value of 19 ions/cm in normal air agrees with the minimum ionization found for electrons. C. T. R. Wilson[3] also counted primary ions in nine straight tracks of unknown energy which presumably were cosmic-ray mesotrons and obtained a value of 20 ions/cm. In the present experiment the primary ionization of both cosmic-ray electrons and mesotrons was measured.

[1] E. J. Williams and F. R. Terroux, Proc. Roy. Soc. **A126**, 289 (1930).
[2] H. K. Skramstad and D. L. Loughridge, Phys. Rev. **50**, 677 (1936).
[3] C. T. R. Wilson, Proc. Roy. Soc. **A104**, 192 (1923).
[4] P. Kunze, Zeits. f. Physik **83**, 1 (1933).

APPARATUS

The cloud chamber used in obtaining the photographs was 30 cm in diameter and 30 cm deep with a magnetic field of about 1000 oersteds from two Helmholtz coils. Illumination was provided by four 6000-lumen medium bi-post street lamps which were operated at about 70 volts for one second. Four sets of four-inch condensing lenses were adjusted to give slightly convergent beams of light which entered the cloud-chamber cylinder near the rear and passed out of the cylinder near the front, making an angle of 50° with the axis. Photographs were taken on Agfa Ultraspeed 35-mm film with a stereoscopic camera equipped with 5-cm lenses and a curtain type shutter. The lenses were focused for different distances (54 and 59 cm) in order to make use of a large portion of the cloud-chamber volume. With lens apertures of f : 8 the depth of focus of each lens was about 5 cm. The program of operations involved in taking photographs was controlled by a cam system driven by an induction motor, the speed of which was essentially 1800 r.p.m. A pulse of x-radiation could be sent into the chamber at any desired time during the program in order to see if the chamber was still sensitive. The pulse came from a Coolidge type tube during the application of a 15,000-volt a.c. pulse to the target.

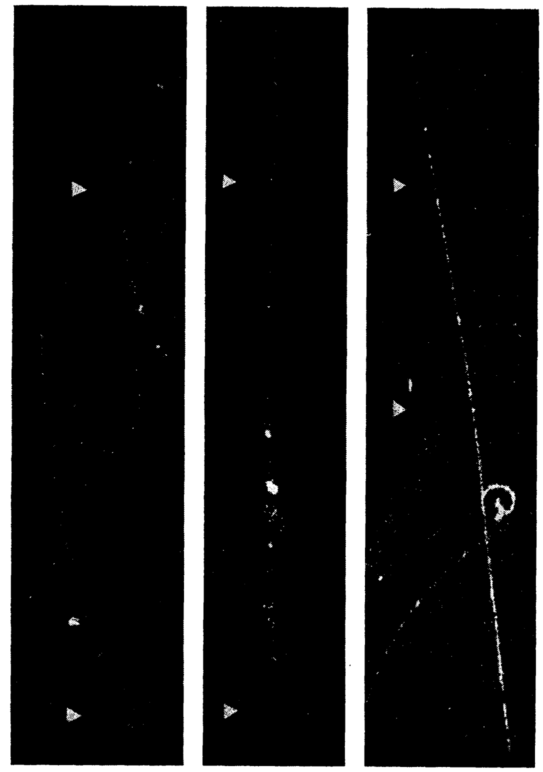

FIG. 1. Post expansion tracks of cosmic rays. There are two electron tracks in the left picture, a mesotron in the middle picture, and a proton and two electrons in the right picture. A pre-expansion diffuse track also appears in the right picture. The index marks represent 5 cm in the cloud chamber.

PROCEDURE

The chamber was filled with helium gas and the saturated vapor from a 1:3 water-ethanol liquid mixture, to a total pressure of 1.2 atmos. Such a gas mixture gives about seven primary ions per centimeter of cosmic-ray path at the expanded pressure and since the magnification was about one-tenth, one obtains about seven droplet images per millimeter on the film. The mean image diameter was 0.003 cm so that the correction factor for overlapping of images is 1.1. In using the cloud chamber to determine ionization one must consider the efficiency of ions as condensation nuclei at the time the track in question was formed. In measuring primary ionization only post-expansion tracks can be used because a large cloud chamber cannot conveniently be expanded quickly enough to produce a truly sharp track. Expansions are therefore made at random and sharp tracks in good focus sometimes occur. The frequency of occurrence depends on the usable sensitive time of the chamber, which in turn may depend on the velocity of fall of the drops or on the actual sensitive time of the chamber. In the case of the present experiment, the maximum sensitive time for condensation on about 50 percent of the positive ions was 0.3 sec. The dependence of condensation efficiency on expansion ratio has been determined by Bagley[5] and by Nielsen[6] and the dependence of sensitive time on expansion ratio by the author.[7] From such information the fraction of the sensitive time during which the condensation efficiency on ions remains greater than say 90 percent can be found. This fraction is approximately one-third

[5] G. D. Bagley, Phys. Rev. **56**, 851 (1939).
[6] C. E. Nielsen, Ph.D. thesis, University of California (1941).
[7] W. E. Hazen, Rev. Sci. Inst. **13**, 247 (1942).

and the usable sensitive time, when we allow ten percent for uncertainty, was therefore 0.1 sec. in the present experiment. The sensitive time was checked after every few expansions and the chamber was adjusted to keep the sensitive time greater than 0.3 sec.

Since the drops required 0.15 sec. or more to grow to photographable size, under the conditions existing in this experiment, the camera shutter was tripped 0.25 sec. after the expansion. At the end of 0.25 sec. a water-alcohol drop in helium falls two cm/sec. and as a result the image moves 0.2 cm/sec. A shutter speed of 1/150 sec. therefore allows an image motion of only 0.0013 cm (less than one-half the image diameter) and the resulting elongation is scarcely noticeable. With this shutter speed good photographic images were obtained with lens apertures of f:9; larger apertures increase the image size and hence lower the resolution. Tracks of particles that passed through the cloud chamber immediately after the expansion were not appreciably distorted by their fall of 3 mm which occurred before the photograph was taken.

The position and angle of the tracks were determined by reprojection through the camera onto a screen which was adjusted so that the two images coincided. This method allowed the determination of track lengths to within a few percent. The apparent curvature of the images of straight lines that did not pass through the camera axis was found to be negligible (40-m radius of curvature). Reproductions of some of the photographs are shown in Fig. 1.

TABLE I. Figures used in estimating mean primary ionization per cm for a group of cosmic rays with $H\rho > 10^6$. Blackett gives the spectrum in terms of energy E. Since the values for E were obtained from $E=300H\rho$ and since there are significant departures from this simple relation for mesotrons in the lower energy range, Blackett's values of E were changed to $H\rho$ by dividing by 300.

$H\rho$ group	Fraction of sea level radiation	Fraction of particles with $H\rho>10^6$	Mean ionization	Products of columns one and two
$1-3\times10^6$	0.142	0.213	7.7	1.64
$0.3-1\times10^7$	0.276	0.414	8.5	3.52
$1-3\times10^7$	0.173	0.260	9.3	2.42
$0.3-1\times10^8$	0.051	0.077	10.3	0.80
$>10^8$	0.024	0.036	11.7	0.42
	Expected mean ionization			$=8.80$

RESULTS

Out of 180 photographs, 46 tracks of high velocity particles were obtained which were in sharp focus for at least several centimeters. These 46 tracks fall into two distinct groups; one group consists of 21 electrons in the $H\rho$ range from 2.5×10^3 to 3×10^4, the other of 25 particles with $H\rho\geq10^6$. The electron group extends over an energy band which is roughly centered on the minimum and is sufficiently narrow to allow consideration of the ionization of all the particles as a group.

The weighted mean for the specific primary ionization of the 21 electrons is 7.33 ions/cm with a probable error of the mean of 1.6 percent or a mean error of 11 percent for one observation. The mean statistical error $1/\sqrt{n}$ for the individual observations averages 13 percent; the main error in the observations is therefore statistical. The weighted mean for the 25 particles with $H\rho\geq10^6$ is 7.23 ions/cm with a probable error of the mean of 1.7 percent or a mean error of 12.7 percent for one observation. Again the mean statistical error for individual observations averages 13.4 percent and the main error is therefore statistical.

The close agreement between the specific ionization for the electrons, which are known to have velocities near that for minimum ionization, and the specific ionization for the group of particles with $H\rho\geq10^6$, indicates either that nearly all of the latter particles had an $H\rho$ less than 6×10^6 or that the primary ionization does not increase as rapidly with velocity as the theory predicts. The energy spectrum for particles with $H\rho$ greater than 10^6, as determined by Blackett,[8] is given in Table I together with the ionization[9] predicted by assuming a minimum

[8] E. J. Williams, Proc. Roy. Soc. **A172**, 206 (1939).

[9] The value for the ionization ($\bar{I}$) to be multiplied with the fractional number of particles in a given energy band can be approximated as follows for the higher energies. The fractional number of particles df with energy between E and $E+dE$ is essentially $df=cdE/E^2$, where $c=$constant. The ionization I of particles beyond the minimum is given approximately by $I=k\log E/E_0$, where k and E_0 are constants. Then $\bar{I}=\int_1^2 I df/\int_1^2 df$ and if all the quantities are expressed in terms of E

$$\log \bar{E}/E_0=\frac{E_2\log E_1/E_0-E_1\log E_2/E_0}{E_2-E_1}+1,$$

where $k\log\bar{E}/E_0=\bar{I}$. For $E_2=nE_1$

$\bar{E}=eE_1/n^{1/(n-1)}$ (e is the base of natural logarithms)

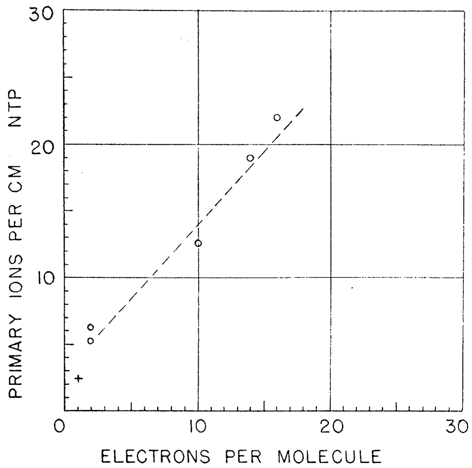

FIG. 2. Experimental values for the minimum primary ionization per centimeter in H_2, He, Ne, N_2, and O_2 are indicated by the circles (the upper circle at abscissa 2 is for He). The calculated value for atomic hydrogen is indicated by the cross. The straight line was used merely to estimate values for other molecules.

ionization of 7.3 and by assuming that the proportional increase in ionization with $H\rho$ is the same as that for atomic hydrogen.[10] Since the logarithmic rise obtained experimentally by Corson and Brode[11] for the probable ionization in nitrogen is about the same as the calculated value for atomic hydrogen, the second assumption just noted seems amply justified. By weighting each ionization with the corresponding fractional number of particles in that part of the spectrum, and by summing the resulting products, one obtains 8.80 ions/cm as the expected value for the mean ionization. This result is 22 percent larger than the observed value of 7.23 ions/cm, whereas the probable error of the mean is only 1.7 percent. Fermi[12] has shown that polarization of the medium reduces the ionization, but the effect is negligible in air for energies less than 10^{10} ev. There are so few particles with energy greater than 10^{10} ev that even if one assumes no increase whatsoever for the ionization in this range, the mean ionization should still be 8.70 ions/cm.

The above values are for the ionization in the helium, alcohol, and water atmosphere existing in the cloud chamber at a total pressure of 1.03 atmos. and a temperature of 22°C. The ionization in the alcohol and water vapor can be estimated from their partial pressures and their electron densities. If one plots the values for the ionization in H_2, Ne, N_2, and O_2 obtained by previous experiments[1,2] as a function of the number of electrons per molecule the ionization of other elements can be estimated from the resulting curve (Fig. 2). Thus for C_2H_5OH the value for I is 33 or 42 ions/cm depending on whether one chooses to extrapolate to $n=26$ electrons per molecule or to add values of I for C_2, $3H_2$, $\frac{1}{2}O_2$. The latter method seems more reasonable and was adopted. The partial pressures of H_2O and C_2H_5OH in equilibrium with a 1:3 liquid mixture were obtained from Gautier and Ruark.[13] The final value for He at N.T.P. is 6.5 ions/cm.

Three of the observed tracks had ionization and momentum consistent with protonic mass. Two of these were diffuse and appreciably curved in the magnetic field; the third (Fig. 1) was straight on each side of a bend produced by a close nuclear encounter but a delta-ray aided in the identification. These three particles constituted approximately one percent of the radiation in the $H\rho$ band from 10^6 to 3×10^6.

The magnet used in the investigation was designed and assembled by William Fretter. A detailed description will probably appear elsewhere at some later date. In concluding, the author wishes to express his appreciation to Professor R. B. Brode for the suggestion of the problem and for advice in carrying out the research.

and for $n=3$, $\bar{E}=1.6E_1$ or for $n=\infty$, $\bar{E}=eE_1$. The particles must be considered in several energy bands because the energy spectrum does not follow the $1/E^2$ distribution closely: the spectrum has a maximum at $E=10^9$ and falls off less rapidly, than $1/E^2$ for higher energies.

[10] E. J. Williams, Proc. Roy. Soc. **A139**, 163 (1933).

[11] R. B. Brode, Rev. Mod. Phys. **11**, 222 (1939).

[12] E. Fermi, Phys. Rev. **57**, 485 (1940).

[13] T. N. Gautier and A. E. Ruark, Phys. Rev. **57**, 1040 (1940).

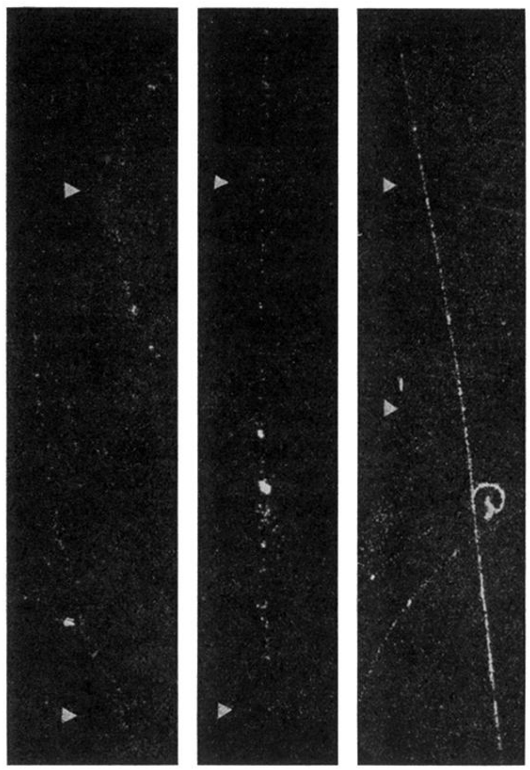

FIG. 1. Post expansion tracks of cosmic rays. There are two electron tracks in the left picture, a mesotron in the middle picture, and a proton and two electrons in the right picture. A pre-expansion diffuse track also appears in the right picture. The index marks represent 5 cm in the cloud chamber.