Cloud-Chamber Study of Collision Electrons in Equilibrium with Mesons

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A 30-cm counter-controlled Wilson cloud chamber contained a tungsten plate of 3.81-cm thickness. A block of lead either 2.54 or 7.62 cm placed above the cloud chamber enabled a distinction to be made between mesons and electron showers. 601 meson tracks were observed (no magnetic field), 497 of which traversed the tungsten plate. From these, the percentage of fast collision electrons in equilibrium with mesons in tungsten and lead was found to be 10.5 percent and 8 percent, respectively, in good agreement with the theories of Bhabha, and Tamm and Belenky. 143 collision electrons with energy range from 13 kev to 175 kev were produced by meson tracks in the gas and indicated a $1/E^2$ differential spectrum. Some interesting individual events associated with mesons are described.

I. RELATION BETWEEN SOFT AND HARD COMPONENT AT SEA LEVEL

It is now generally believed that the soft component of cosmic rays at sea level consists of electrons, and that the bulk of these electrons arise from the mesons, or penetrating component of cosmic rays. Electrons arise from mesons by three different processes. (1) Mesons create collision electrons[1] by elastic Coulomb field encounters with atomic electrons. (2) Mesons which pass very close to atomic nuclei radiate quanta. The quanta can give rise to electrons by materialization. (3) It is believed that the radioactive decay of the meson liberates an electron and a neutrino. Energetic electrons arising from all three of these processes give rise to cascade progeny. These electrons make up the soft component, which is in equilibrium with the meson component at sea level.

Previous investigators have measured the amount of soft component in equilibrium with the hard component by means of Geiger-Müller counters. But results published in the literature are widely divergent and depend on the conditions of the individual experiment. A consistent picture seems to be that 30–43 percent of cosmic radiation at sea level in free air is soft component.[2] But when the measurements are made under 6 cm Pb, or under ≈ 30 m H_2O equivalent of soil, the decay electrons and progeny are all absorbed, leaving ≈ 10 percent due to collision electrons.[3]

The following factors affect the results of counter experiments. The thickness of the counter walls is very critical because of the large proportion of slow electrons in cosmic rays. By using counters with very thin walls, Danforth and Lipman[4] have shown that the number of cosmic rays between 5×10^6 ev and 10^7 ev is $\frac{1}{8}$ of the total intensity above 10^7 ev. The presence of a roof over the apparatus increases the soft component, and nearby walls can cause side showers which can trip the counters without penetrating the absorber. The geometrical arrangement of the counters affects the experiment strongly since the hard component decreases much more rapidly with zenith angle than does the soft component.[5] Furthermore, a Geiger counter will always count as one particle, two particles which simultaneously fall within its cross-sectional area. So it is easy to see why almost every different counter experiment gives

[1] Collision electrons are sometimes called "knock-ons" or "delta-rays."

[2] W. M. Nielsen and K. Z. Morgan, Phys. Rev. **54**, 245 (1938); K. Greisen, Phys. Rev. **61**, 212 (1942).

[3] P. Auger (Comptes rendus **206**, 346 (1938)) reports that under 1 m H_2O equivalent plus 6 cm Pb, and also 30 m H_2O equivalent soil, 9 percent of soft component is in equilibrium with the penetrating component.

[4] W. E. Danforth and M. R. Lipman, J. Frank. Inst. **217**, 73 (1934). The twofold coincidence set used required particles to penetrate a thickness of only 0.36 gram/cm² to be recorded. Setting the lower limit of cosmic-ray energies at 5×10^6 ev excludes practically all electrons from natural radioactivity.

[5] The soft component is more strongly scattered in the atmosphere, hence decreases less rapidly with zenith angle. Beneath 30 meters of soil, Auger and Grivet (Rev. Mod. Phys. **11**, 232 (1939)) found that the soft component diminished only ≈ 20 percent between 0° and 60° zenith angle, while the hard component diminished ≈ 65 percent for the same angles.

a different value for the amount of soft component in equilibrium with the hard component.

The present experiment attempts to simplify the picture by studying electrons produced by mesons by only the first of the above-listed three processes, namely, collision electrons. A Wilson cloud chamber is used to detect the meson and the collision electrons. The cloud chamber enables positive identification of all the collision electrons accompanying the meson in the chamber, and is not subject to the uncertainties of Geiger counter experiments listed above.

In this experiment electrons arising from bremsstrahlung quanta were unimportant in number and those from radioactive decay were not observed. Bhabha[6] has shown from theoretical considerations that the amount of soft component produced by bremsstrahlung quanta is negligible compared to that produced by collision electrons, if the mesons have mass $\geqslant 100$ electrons masses. All the mesons observed here traversed the chamber, hence could not have decayed. A discussion of the amount of soft component arising from decay electrons has been given by Rossi and Greisen.[7]

In this paper the terms "penetrating component" and "mesons" are used synonymously. However, it is possible that as much as 5 percent of the penetrating component may consist of protons.

II. EXPERIMENTAL APPARATUS

The apparatus consisted of a Wilson cloud chamber whose expansions were controlled by a threefold Geiger counter-coincidence system, as shown in Fig. 1. Between the upper two counters and the cloud chamber was a block of lead. This was 7.62 cm thick for most of the expansions, but was reduced to 2.54 cm for others. The upper two counters were glass walled with a copper cylinder, while the small counter was made of brass. All counters were filled with ethyl alcohol and argon gas in the conventional way. The cross-sectional area of the upper counters was 22.8×4.13 cm^2 while that of the small brass counter was 10×0.795 cm^2.

The cloud chamber was 30 cm in diameter, of which a vertical strip 10 cm wide$\times$30 cm high was visible. The depth of the illuminated region was 4 cm. A horizontal brass box was built into the front of the chamber similar to the arrangement used by Code.[8] The interior of the brass box was accessible without dismantling the chamber. Contained in the box were 6 bars of tungsten and the brass-walled Geiger counter. The six bars had a total thickness of 3.81 cm. Because of the high density of tungsten (19.3 grams/cm^3), a particle which traverses 3.81 cm suffers an ionization loss equal to that from 6.8 cm of Pb. The cloud chamber was filled with undiluted ethyl alcohol and pure argon gas to a total pressure of 995 mm Hg. The diaphragm and expansion valve were similar to that used by Jones and Hughes.[9] A new expansion ratio backstop plate was built. This plate was adjusted by three screws so that it could control distortions as well as the expansion ratio.

The photographic system consisted of a 35-mm commercial camera and three plane mirrors for

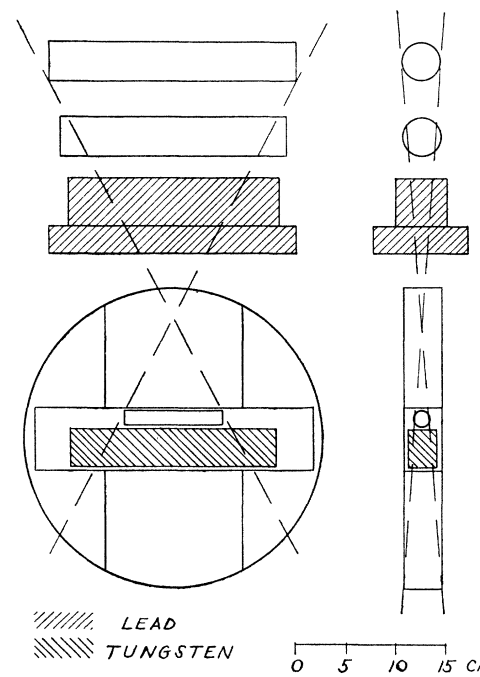


FIG. 1. Arrangement of cloud chamber and triple-coincidence system, showing the lead block above the chamber and the tungsten plate in the chamber.

[6] H. J. Bhabha, Proc. Roy. Soc. London **A164**, 257 (1938).

[7] Bruno Rossi and Kenneth Greisen, Phys. Rev. **61**, 121 (1942).

[8] F. Leslie Code, Phys. Rev. **59**, 229 (1941).

[9] Haydn Jones and Donald Hughes, Rev. Sci. Inst. **11**, 79 (1940).

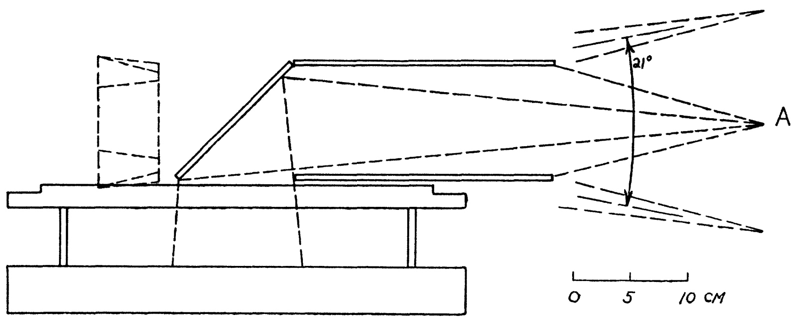


FIG. 2. Stereo-optical diagram, showing cloud chamber, 45° mirror, and two parallel mirrors, enabling a single lens at A to take three pictures.

taking stereo pictures. The lens was a Zeiss f: 2.8 and 50-mm focal length. Figure 2 shows the optical system, which was designed to enable the cloud chamber to operate between the pole pieces of the cosmic-ray magnet at the University of Chicago. During this experiment, however, it was not possible to operate the magnet. The camera looks into the mirror placed at 45° to the plane of the chamber and takes a direct picture. The two plane mirrors parallel to the plane of the chamber enable the camera to view the chamber at an angle of $10\frac{1}{2}°$ on either side of the direct picture. Any two of the three pictures can be used for stereo comparison. When the film is projected on a plane surface, three images appear. For points on the outer two images, their separation is proportional to the distances normal to the plane of the chamber. A calibration was made by photographing the cloud chamber with fine threads on its front and back surface. Thus stereo distances could easily be measured upon projection on a plane surface, without the use of a stereo-calibrator.

The illumination of the cloud chamber was obtained with the use of medium bi-post street lamps. Nine such lamps were mounted on units consisting of street lamp, spherical mirror, and double convex lens. Both the mirror and lens were of short focus, so that the optical system gathered approximately 2.5 out of a possible 4π steradians of luminous flux. The street lamps were of clear glass and the filament was shaped into a slender helix of diameter 0.32 cm and length 3.81 cm. These dimensions were proportional to those of the cross section of the chamber, so that an enlarged image of the filament filled the entire chamber. The image was focused beyond the chamber, so that while passing through the chamber, the light was convergent and out of focus. The beams from nine such units provided a solid bank of illumination for the cloud chamber. The convergent character of the beams was essential in keeping light off the background.

The street lamps were rated at 6000 lumens, drawing 6.6 amperes at 49 volts under normal operation. In this experiment, the lamps were flashed at 77 volts, since banks of three lamps were connected in series across 230 volts, a.c. For each picture the current was left on for $\frac{1}{3}$ second. The make contact was established by ordinary $\frac{3}{16}''$ tungsten contact points, but break was established by a cut-out relay. This relay was actuated by a thyraton, controlled by an electronic time delay circuit.

III. COLLISION ELECTRONS IN EQUILIBRIUM WITH MESONS IN TUNGSTEN

These data result from 497 pictures in which a meson traverses the tungsten plate. That the primary particle was a meson (or other heavy particle) is certain because electrons below 10^{10} ev would not penetrate 3.81 cm of tungsten. In addition, the mesons had to penetrate either 7.62 or 2.54 cm of Pb above the cloud chamber. Above the apparatus was only a thin roof. The electrons which accompany mesons emerging from the bottom of the tungsten plate give a true picture of equilibrium conditions within the tungsten. The results in Table I give the number of fast and slow electrons accompanying the mesons out of the tungsten. Electrons whose tracks were straight were classed as fast electrons. Since their tracks showed no scattering

TABLE I. No. of collision electrons N accompanying 497 mesons emerging from 3.81 cm of tungsten.

	N fast ($E>1$ Mev)	N slow ($E<1$ Mev)	N total (N fast $+N$ slow)	N slow heavy particles (short dense tracks)
	52	22	74	3
Percent of mesons traversing tungsten	$52/497=10.5\%$	$22/497=4.4\%$	$74/497=14.9\%$	$3/497=0.6\%$

TABLE II. Collision electron showers accompanying 497 mesons emerging from 3.81 cm of tungsten.

No. of showers	Particles per shower
Fast electron showers ($E>1$ Mev)	
3	2
1	3
2	5
Slow electron showers ($E<1$ Mev)	
3	2

in the gas, their kinetic energy was above 1 Mev. Electrons whose tracks did show scattering in the gas were classed as slow electrons of kinetic energy <1 Mev. A few short, dense tracks were observed, which must have been caused by heavy particles.

Most of the electrons which accompanied the mesons occurred singly, but cases of showers of collision electrons occurred also. The results are listed in Table II.

Some of the slow electrons probably arose from radioactive contamination. Hence the data presented on slow collision electrons are not as accurate as those for the fast collision electrons.

Collision electrons were also created in the lead block (either 2.54 or 7.62 cm thick) above the cloud chamber, and in the glass ring at the top of the chamber. These data are not as accurate as those for the collision electrons arising from the tungsten plate because the lead block was 4.45 cm above the top of the cloud chamber, and the glass ring (2 grams/cm^2) was not thick enough to allow equilibrium. In spite of these inaccuracies these data do give a good idea of the number of collision electrons arising in such cases, and are presented in Table III.

The collision electrons from the lead had to pass through the glass ring, which set a lower limit to the energy of the fast electrons. Electrons which showed no scattering in the gas had $E>1$ Mev in the chamber. But 4.3 Mev was necessary to penetrate the glass ring, or a total kinetic energy >5.3 Mev when emerging from the lead. Again the data on slow electrons are subject to inaccuracies due to the presence of such electrons from radioactive contamination.

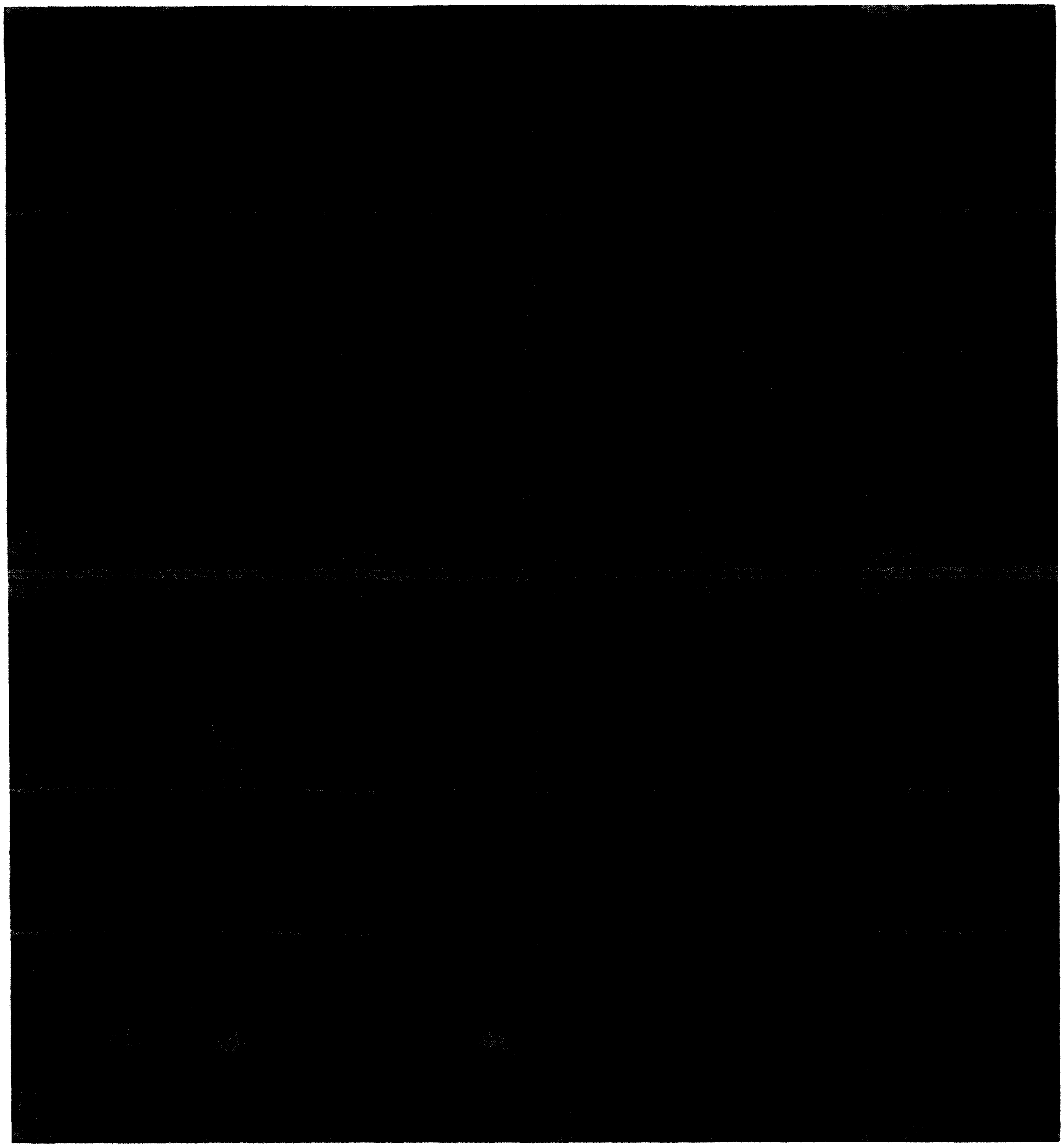
Table III gives the results of 601 pictures in which mesons traversed the lead and glass ring. This number is larger by 104 than the number of mesons which traversed both the lead and the tungsten, because (a) some of the mesons traversed the top half of the chamber at such an angle as to pass out of view below the tungsten and (b) some of the mesons stopped in the tungsten. Showers of electrons sometimes tripped the threefold coincidence system, but they were easily distinguished from the mesons, and were not counted. Figures 3, 4, and 5 show typical collision electrons arising from the tungsten or lead.

From theoretical considerations, the number of collision electrons which accompany mesons as they traverse different substances has been calculated by two different authors. Tamm and Belenky[10] give the results in the form of an

[10] Ig. Tamm and S. Belenky, J. Phys. Acad. Sci. U.S.S.R. 1, 177 (1939).

TABLE III. No. of collision electrons N accompanying 601 mesons traversing the lead block and upper glass ring of cloud chamber.

Lead			Glass			
N fast ($E>5.3$ Mev)	N slow ($4.3<E<5.3$ Mev)	N total (N fast$+N$ slow)	N fast ($E>1$ Mev)	N slow ($E<1$ Mev)	N total (N fast$+N$ slow)	
48	10	58	13	3	16	
$48/601=8\%$	$10/601=1.7\%$	$58/601=9.7\%$	$13/601=2.2\%$	$3/601=0.5\%$	$16/601=2.7\%$	Percent of mesons traversing lead or glass



FIGS. 3–6.

FIG. 3. A meson penetrates 3.81 cm of tungsten and is accompanied by a collision electron. The central picture corresponds to a direct view while the two outer pictures are used for stereo comparison.

FIG. 4. A collision electron arising in the lead block above the cloud chamber accompanies the meson. The electron is stopped, but the meson penetrates the tungsten without multiplication.

FIG. 5. An electron shower of 5 particles accompanies the meson traversing the tungsten.

FIG. 6. Low energy collision electrons produced in the gas. Three such electrons arise from the meson track in the top half of the chamber.

integral spectrum $N(E)$, of the mean number of electrons of energy greater than E which accompany mesons in air and Pb. Bhabha's[6] results give two points of the integral spectrum, namely, $N(E_c)$ the number of electrons of energy greater than the critical energy, and $N<(E_c)$ the number

TABLE IV. Theoretical and experimental values of the percent of electrons $N(E)$ of energy greater than E which accompany mesons in lead.

Theory			Experiment	
Bhabha	Tamm and Belenky	Tamm and Belenky		
$E_0=10^{10}$ ev $\mu=100m$	$E_0=10^{10}$ ev $\mu=100m$	$E_0=1.7\times10^9$ ev $\mu=160m$	Tungsten	Lead
E_c for Pb, 10 Mev $N(E_c)=9.0\%$	E_c for Pb, 10 Mev $N(E_c)=5.3\%$	E_c for Pb, 10 Mev $N(E_c)=2.3\%$		
	$E=5.3$ Mev $N(E)=8.1\%$	$E=5.3$ Mev $N(E)=4.0\%$		$E=5.3$ Mev $N(E)=8.0\%$
	$E=4.3$ Mev $N(E)=9.7\%$	$E=4.3$ Mev $N(E)=5.0\%$		$E=4.3$ Mev $N(E)=9.7\%$
	$E=1.3$ Mev $N(E)=18.8\%$	$E=1.3$ Mev $N(E)=11.0\%$		
			$E=1$ Mev $N(E)=10.5\%$	
$N(E)=19.0\%$ Total			$N(E)=14.9\%$ Total	

of electrons of energy less than the critical energy, the sum of these two giving N total. The results are given for air or water, and lead.

The interaction between mesons and atomic electrons of matter is due mostly to Coulomb forces. But when a meson passes very close to an electron, as happens in the production of high energy collision electrons, the spin of the meson becomes all important.[11] From other experiments in cosmic rays spin 1 seems unlikely for the meson, and spin 0 and spin $\frac{1}{2}$ give essentially the same collision cross sections. So, in this sense, the integral spectrum of collision electrons may be said to be spin independent.

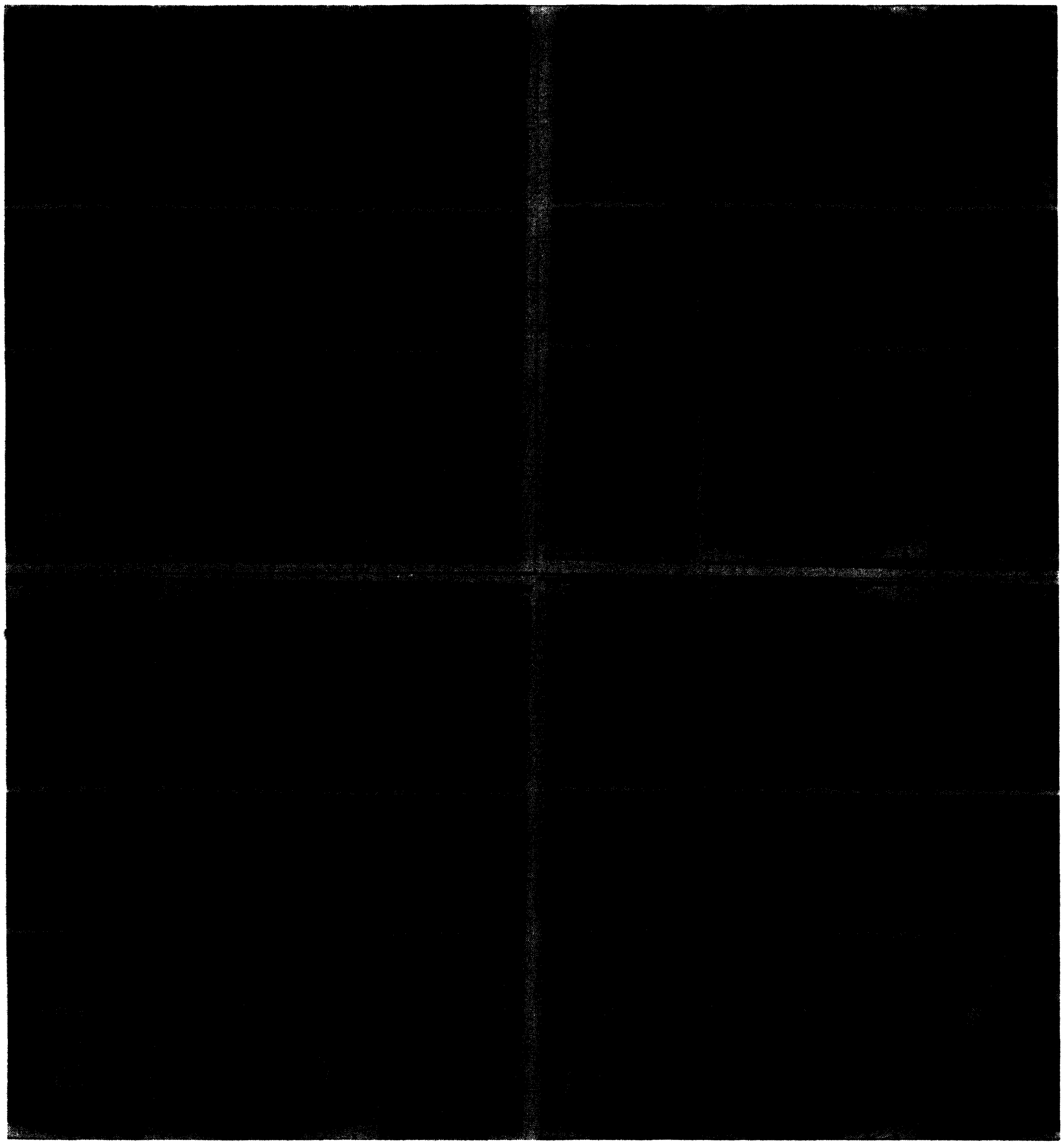
Tamm and Belenky have shown that the shape of the integral spectrum $N(E)$ is rather insensitive to variations of mass and energy of the generating mesons. They have calculated $N(E)$ for two kinds of primary mesons. (a) $\mu=100m$ and $E_0=10^{10}$ ev; (b) $\mu=160m$ and $E_0=1.7\times10^9$ ev (μ=mass of meson; m=mass of electron; E_0=energy of generating meson) and find that the curves differ by only a few percent. Hence the integral spectra $N(E)$ are applicable to sea level mesons, whose spectrum has a maximum at $\approx1.5\times10^9$ ev. Tamm and Belenky further show that the customary neglect of ionization losses for electrons of greater than critical energy reduces up to 50 percent the number of electrons in the vicinity of the critical energy.

The integral spectrum $N(E)$ of collision electrons decreases monotonically with increasing energy E, and decreases faster for lead than for air. The production of collision electrons is proportional to the density of electrons, hence is proportional to Z. But the cascade absorption of high energy collision electrons introduces a factor $1/Z^2$, so that the number of high energy collision electrons in different elements falls off roughly as $1/Z$.

The experimental and theoretical values of the percentage of electrons accompanying mesons in lead are given in Table IV. Since the atomic number of tungsten (74) is not far different from that of lead (82), the experimental values for tungsten may be compared with the theoretical values for lead. The experimental values from the glass ring cannot be compared with the theory since the glass ring was not thick enough to allow equilibrium. The energy and mass of the mesons used in the theoretical calculations are given in the table.

In view of the scarcity of theoretical and experimental values of $N(E)$, a comparison is

[11] The cross section for production of high energy collision electrons by mesons is given for spin 0, $\frac{1}{2}$, and 1 by B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 244 (1941).



FIGS. 7–8, 10–11.

FIG. 7. Two collision electrons arise from the meson track in the bottom half of the chamber. One electron passes out of view.

FIG. 8. Three collision electrons from a single meson. The meson produces a collision electron in the gas near the top of the tungsten plate, and penetrates the tungsten with a small deflection due to scattering. A collision electron also arises from the lead above the chamber and gives rise to a secondary collision electron in the gas near the top of the photograph.

FIG. 10. Shower of two mesons arising from the 7.62 cm Pb above the chamber penetrates the tungsten without multiplication. One of the tracks is slightly blurred in the botton half of the chamber due to motion of the gas.

FIG. 11. Possible nuclear disintegration arising in the tungsten. The penetrating particle shows very small scattering (2°) in the 3.81-cm tungsten plate. The heavily ionizing particle appears to arise in the center of the tungsten, and gives rise to two low energy collision electrons in the gas. These can be seen best in the right-hand picture.

made by interpolation. Recall that $N(E)$ is a decreasing function of E. The experimental data from tungsten are smaller than all of the interpolated theoretical values, but do not differ much from that of Tamm and Belenky for E_0 1.7×10^9 ev. The experimental data from lead agree very well with Tamm and Belenky for E_0 10^{10} ev. These values are greater than Tamm and Belenky for E_0 1.7×10^9 ev but are only slightly smaller than interpolated values of Bhabha.

Bhabha[6] has calculated also the probabilities of mesons being accompanied by shower electrons of energy greater than critical energy. Experimental values obtained from Table II are compared with Bhabha's values in Table V.

The agreement is rather close considering the small number of showers observed. A more detailed study of collision electron showers has been made by Lovell.[12]

IV. LOW ENERGY COLLISION ELECTRONS PRODUCED IN THE GAS OF THE CLOUD CHAMBER

One hundred and forty-three collision electrons were observed arising in the gas of the cloud chamber. These had ranges in the gas from 2 mm (the smallest discernable) to 130 mm. Figures 6, 7, and 8 show typical collision electrons produced. The cloud chamber was filled with ethyl alcohol, C_2H_5OH (vapor pressure at room temperature 45 mm Hg) plus 950 mm Hg of argon to make a total pressure of 995 mm Hg. To a good approximation, the gas can be considered entirely argon, having a density of 2.33×10^{-3} g/cm^3. The 143 collision electrons were produced by 601 mesons which traversed the chamber for an average path length of 17.11 cm in the gas. Thus the total meson path length was 103.82 meters, corresponding to a thickness of 24.2 grams/cm^2 of argon.

The range in cm of the collision electrons multiplied by the density of the gas gives the range in grams/cm^2 of argon. From natural

TABLE V. Probabilities of mesons in lead being accompanied by showers of electrons.

No. of electrons in shower	2	3	4	5
Bhabha's values	0.014	—	0.0057	0.0038
Experimental values	0.006	0.002	—	0.0040

[12] A. C. B. Lovell, Proc. Roy. Soc. **A172**, 568 (1939).

radioactivity, the range of beta-rays in grams/cm^2 of aluminum *versus* energy is well known.[13] Since aluminum lies close to argon in the periodic table, the experimental beta-ray curves can be used to determine the energies of the collision electrons. The values deduced for low energy collision electrons may be high by a factor not exceeding 1.5 because the true scattered length of track measured in the cloud

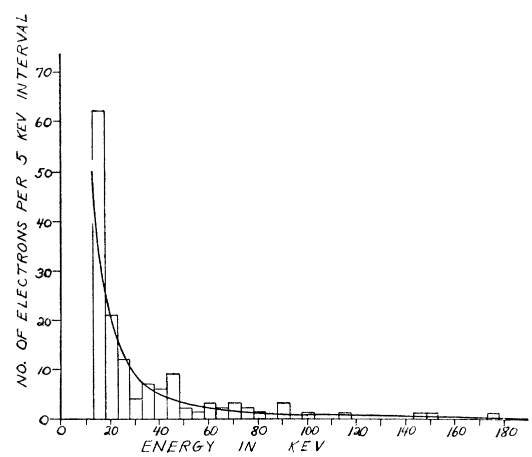


FIG. 9. Collision electrons produced in the gas of the cloud chamber by 103.82 meters of meson track. The blocks represent experimental points, and the solid curve the Rutherford formula.

chamber is longer than the equivalent aluminum range.

In this manner the energies of one hundred forty-three collision electrons were tabulated. The energy spectrum pictured in Fig. 9 was then made by means of a block diagram, the height of each block being proportional to the number of collision electrons having energies in a given 5-kev spread. The solid curve in Fig. 9 is the theoretical value of the number of collision electrons given by the Rutherford formula (discussed below). The agreement between theory and experiment is quite good, both as to the shape of the spectrum and the total number of electrons in the spectrum. At the lowest energy interval, an additional number of electrons is observed, due to Auger electrons arising from krypton impurities of the argon gas.[14]

[13] Franco Rasetti, *Elements of Nuclear Physics* (Prentice-Hall, New York, 1936).

[14] The K-absorption limit for krypton is 14.3 kev, giving an Auger electron range of ≈ 2 mm in the cloud chamber. The K limit for argon is 3.2 kev, giving only a blob in the meson track. A rough check of the number

The Rutherford formula was developed to explain ionization losses of radioactive particles. But for low energy transfers it applies equally well to cosmic rays. Such low energy transfers are not dependent on the spin of the meson.[15] The probability that a meson will produce a collision electron in the energy range E, $E+dE$ in traversing a thickness of matter dx grams/cm^2 is given by the Rutherford formula:

$$P(E)dEdx=\frac{2\pi n(Z)r_0^2}{m(A)\beta^2}\frac{dE}{E^2}dx.$$

$\beta=v/c$ velocity of mesotron; m=mass of electron in ev/c^2; r_0=classical electron radius, e^2/mc^2; n=Avogadro's no. For sea level mesons, β may be set equal to unity to a good approximation. The differential spectrum for low energy collision electrons falls off as $1/E^2$ and is indicated by the block diagram of Fig. 9.

Integration of the Rutherford formula gives the total number of collision electrons in the gas:

$$N(E)=\int_{13\text{ kev}}^{200\text{ Mev}}P(E)dE.$$

The lower limit is 13 kev since this is the lowest energy collision electron which can be detected. The integral is practically independent of its upper limit, so long as it is large compared to the lower limit.[16] On setting dx equal to 24.2 grams/cm^2 of argon, integration gives $N=124$ collision electrons. Counting the number of collision electrons in the blocks of the energy spectrum, and substituting the theoretical value for the lowest energy interval, one gets 115. Thus the comparison with the theory is quite good considering the small number of particles observed.

The result of the energy spectrum may be interpreted as follows. In passing through light elements, fast mesons (or electrons) create approximately $120/(24.2)=5$ collision electrons of energy greater than 13 kev per gram/cm^2. Low energy electrons from cosmic rays are more numerous than is generally believed, and play an important part in counter experiments.

V. INTERESTING INDIVIDUAL EVENTS ASSOCIATED WITH MESONS

Pictures obtained show one meson shower, one possible nuclear disintegration, and a number of slow mesons which are stopped in the tungsten.

Out of 591 pictures, 10 show 2 mesons traversing the tungsten in the center of the chamber. Nine of these have mesons which do not show space or time association, hence are not related. (Space association refers to the tracks diverging from some point above the cloud chamber. Time association refers to the age of the tracks. Two sharp tracks cannot be separated by more than 5×10^{-2} sec.) One picture shows two mesons of apparently the same age traversing the tungsten, yet, from the fact that they converge toward a point *below* the cloud chamber, these mesons cannot be related.

The probability for a second meson to accompany the counter controlled expansion of the cloud chamber is easily calculated. The meson flux at sea level has been given as 0.64 per cm^2 per minute per unit solid angle.[17] The cloud chamber had a cross section of $10\times4=40$ cm^2. To penetrate the tungsten, the mesons had to travel at least 20 cm in the chamber, giving a solid angle of $40/400=0.1$. The sensitive time of the cloud chamber being of the order 3×10^{-1} sec. (because of the low sweep field), the probability of a meson traversing for a random expansion was $\approx1.3\times10^{-2}$. This shows that for 600 controlled expansions, 8 should have two meson tracks. This number is of the same order as the number (10) actually observed.

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of electrons in the 13–18 kev interval was made as follows. The number of blobs due to K ionization of argon was found to be ≈60 per meter of track, or 6000 for the total track. Krypton comprises ≈1 percent of argon. Furthermore, K ionization of krypton is only $\frac{1}{2}$ as frequent as argon, because krypton has twice as many electrons. Thus the total number of electrons from K ionization of krypton should be $\frac{1}{2}$ of 1 percent of 6000, or 30. From the 13–18 kev interval of the spectrum it will be seen that the observed number exceeds that given by the Rutherford formula by approximately 30.

[15] See pp. 243 and 244 of reference 11.

[16] The energy E which a collision electron of mass m receives from a meson of mass is determined from classical mechanics

$$E=\frac{2(mc^2)p^2\cos^2\theta}{[mc+(p^2+\mu^2c^2)^{\frac{1}{2}}]^2-p^2\cos^2\theta},$$

where p is the momentum of the meson and θ the angle between the meson and electron track. Setting $\cos\theta$ equal to unity gives $E_{\max}$. For $p=1.5\times10^9$ ev/c, $\mu=10^8$ ev/c^2, $m=5\times10^5$ ev/c^2, the formula gives $E_{\max}=200$ Mev.

[17] See page 571 of reference 12.

Figure 10 shows two mesons of the same age diverging from a point in the 7.62 cm of lead above the chamber and traversing the tungsten. This event is interpreted as a true meson shower. Showers of penetrating particles at sea level have been obtained by counter experiments,[18] but cloud-chamber evidence is quite rare. Janossy[19] has obtained a photograph of 3 mesons penetrating 2 cm of Pb in the cloud chamber without multiplication. At higher altitudes three pictures of meson showers have been reported.[20] Such meson showers may give information on the production of mesons.

Figure 11 may represent a nuclear disintegration. A penetrating particle traverses the tungsten with no appreciable scattering. From the center of its path in the tungsten a heavily ionizing particle emerges, after having itself traversed 1.9 cm of tungsten. The heavily ionizing particle is not appreciably scattered in the gas, and emits two small collision electrons of range ≈ 1 mm. (These can be seen best in the right-hand view.) Near the bottom of the chamber, the heavily ionizing particle passes into the back velvet.

The heavily ionizing particle cannot be an electron. An electron which ionized so heavily would have a low velocity ($\beta < 0.3$); it would be greatly scattered and could have a range of only ≈ 1 cm in the chamber. If the heavily ionizing particle is a proton, it must have an energy of 150 Mev to penetrate 1.9-cm tungsten. If it is a meson, it must have 64 Mev to penetrate the 1.9 cm of tungsten.

The primary particle of Fig. 11 has an energy $\approx 10^9$–10^{10} ev which is deduced from its small scattering (2°) in the 3.81 cm of tungsten. Williams'[21] theory of the scattering of cosmic-ray particles gives a mean scattering angle $\bar{\alpha} = 2.2 \times 10^9$ ev degrees for 3.81 cm of tungsten.

It is unlikely that the heavily ionizing particle is produced by an elastic collision for then the primary would show a greater change in direction, having given up so much of its energy in the process.

The small collision electrons arising from the heavily ionizing particle seem to indicate that the particle is traveling slowly in the gas ($\beta \approx 0.1$). Only a proton could have a range as great as the observed range (10.4 cm in the chamber before passing into the background velvet) with a velocity as low as $\beta = 0.1$.

For most nuclear disintegrations that have been observed, the energy per particle is below 100 Mev and the total energy of all charged particles is less than 200 Mev per disintegration. The single heavily ionizing particle observed here has by itself 150 Mev which seems rather high for a nuclear disintegration. If the heavily ionizing particle is a meson, it has at present no theoretical explanation.

Nuclear disintegrations arising in cloud chambers have been reported by several observers in the past. From 9188 exposures taken at 4300 meters, Anderson[22] reports 6 definite nuclear disintegrations, 5 occurring in a 0.35-cm lead plate and one occurring in the gas of the chamber. The energies of the heavily ionizing particles, where measureable by curvature, were below 50 Mev. From 20,500 counter controlled photographs at sea level, Brode and Starr[23] observed 10 definite nuclear disintegrations arising from the walls or metal plates inserted in the cloud chamber. Several other cloud-chamber nuclear disintegrations have been reported.[24] A great number of nuclear disintegrations have been observed in photographic emulsions.[25]

In regard to the number of slow mesons at sea level, the data can be analyzed in the following way. Of the 601 mesons observed, 71 traversed the top of the chamber diagonally so as to pass out of view in the bottom half. For

[18] L. Janossy, private communication to the University of Chicago; G. Wataghin *et. al.*, Phys. Rev. **57**, 61, 339 (1940); P. Auger and J. Daudin, Phys. Rev. **61**, 549 (1942).

[19] L. Janossy *et al.*, Nature **148**, 660 (1941).

[20] D. J. Hughes, Phys. Rev. **60**, 414 (1941); W. M. Powell, Phys. Rev. **60**, 413 (1941); E. O. Wollan, Phys. Rev. **60**, 532 (1941).

[21] E. J. Williams, Proc. Roy. Soc. **169**, 531 (1939).

[22] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).

[23] R. B. Brode and M. A. Starr, Phys. Rev. **53**, 3 (1938).

[24] P. Auger and P. Ehrenfest, J. de phys. et rad. **8**, 204 (1937); J. Crussard and L. Leprince-Ringuet, J. de phys. et rad. **8**, 213 (1937); P. Kunze, Zeits. f. Physik **83**, 1 (1933); S. Nishida, Proc. Phys. Math. Soc. Japan **19**, 818 (1937). W. M. Powell (Phys. Rev. **61**, 670 (1942)) gives an interesting report of 156 stars obtained from 19,000 expansions at 4300 meters. The stars arise from the argon gas and from five 1-cm Pb plates.

[25] A bibliography of work on nuclear disintegration can be obtained from M. Shapiro, Rev. Mod. Phys. **13**, 58 (1941).

these 71 mesons, it cannot be ascertained whether or not they penetrated the tungsten plate. Of the remaining 530 pictures, 131 were taken with 2.54 cm of Pb above the chamber and 399 were taken with 7.62 cm of Pb above the chamber. Six and 27 of these, respectively, were stopped in the 3.81 cm of tungsten, equivalent to 6.8 cm of Pb. The use of the momentum *vs.* range curves of Rossi and Greisen[26] then gives the following results for sea level mesons: $33/530=6.2$ percent of the penetrating component with momentum between 1 and 3×10^8 ev/c. This is in good agreement with the meson spectrum obtained at sea level by Hughes.[27]

The author deeply appreciates the assistance of Dean A. H. Compton, who has made possible this work. Professor Auger has been of great value in interpreting the experimental results. Messrs. O'Donnel and Kahlberg of the machine shops were of great help in building the apparatus.

[26] See page 249 of reference 11.

[27] D. J. Hughes, Phys. Rev. **57**, 592 (1940).

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A Precision Determination of h/e by Means of the Short Wave-Length Limit of the Continuous X-Ray Spectrum at 20 kv

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A redetermination of h/e by the method of the short wave-length limit of the continuous x-ray spectrum was undertaken in order to obtain further evidence as to the discrepancy among the determinations of atomic constants. The accuracy of the experiment is improved by (1) large primary x-ray intensity, (2) the use of a high resolving power double crystal spectrometer, (3) reduction in background and improvement in the sharpness of the limit by the use of balanced filters, (4) improved accuracy in voltage measurements, and (5) cleaning the target in vacuum. The sources of error both in the measurements and the interpretation of the data are discussed. Our result is $h/e=(1.3786\pm0.0002)\times10^{-17}$ erg sec./e.s.u. This value is found to be in fair, though not complete, agreement with measurements of other atomic constants.

I. THE PRESENT STATE OF OUR KNOWLEDGE OF THE VALUE OF h/e

EVER since absolute x-ray wave-length measurements and the revision of the value of the viscosity of air caused the accepted value of the electronic charge to be raised from the original Millikan value to the neighborhood of 4.8×10^{-10} e.s.u., there appeared a new discrepancy among the values of the natural constants.[1] This discrepancy arises from the fact that values of h/e derived from methods permitting a direct measurement of this quantity failed to agree satisfactorily with the "indirect" value of h/e, i.e., the value derived from other measurements of functions of the atomic constants e, m, and h. The present state of this discrepancy has been thoroughly discussed by Birge,[2,3] Dunnington,[4] Kirchner,[5] and DuMond.[6,7]

The methods for a direct measurement of h/e available at the present time, are: (1) the determination of the short wave-length limit of the continuous x-ray spectrum; (2) the photoelectric effect; (3) the determination of excitation and ionization potentials; (4) the determination of the excitation voltages of x-ray series as compared to the corresponding absorption edges; (5) measurement of the radiation constant c_2. Of these methods at present the first stands out

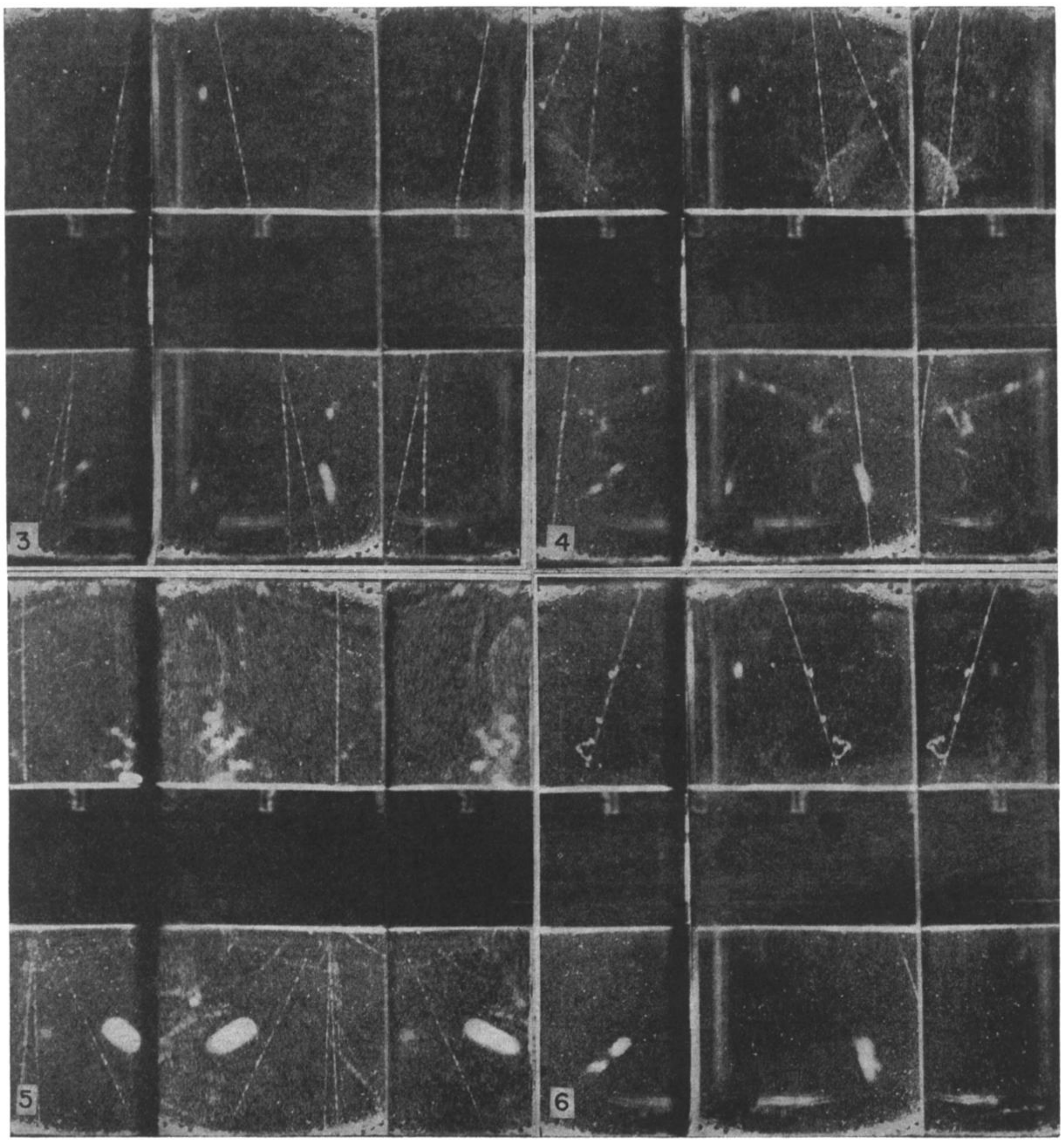
[1] R. T. Birge, Phys. Rev. **48**, 918 (1935).

[2,3] R. T. Birge, *Reports on Progress in Physics*, London Physical Society (in print); R. T. Birge, Rev. Mod. Phys. **13**, 233 (1941).

[4] F. G. Dunnington, Rev. Mod. Phys. **11**, 65 (1939).

[5] Kirchner, "Die Atomaren Konstanten e, m, und h." Ergeb. d. exakten Naturwiss. (1939).

[6,7] J. W. M. DuMond, Phys. Rev. **56**, 153 (1939); J. W. M. DuMond Phys. Rev. **58**, 457 (1940).



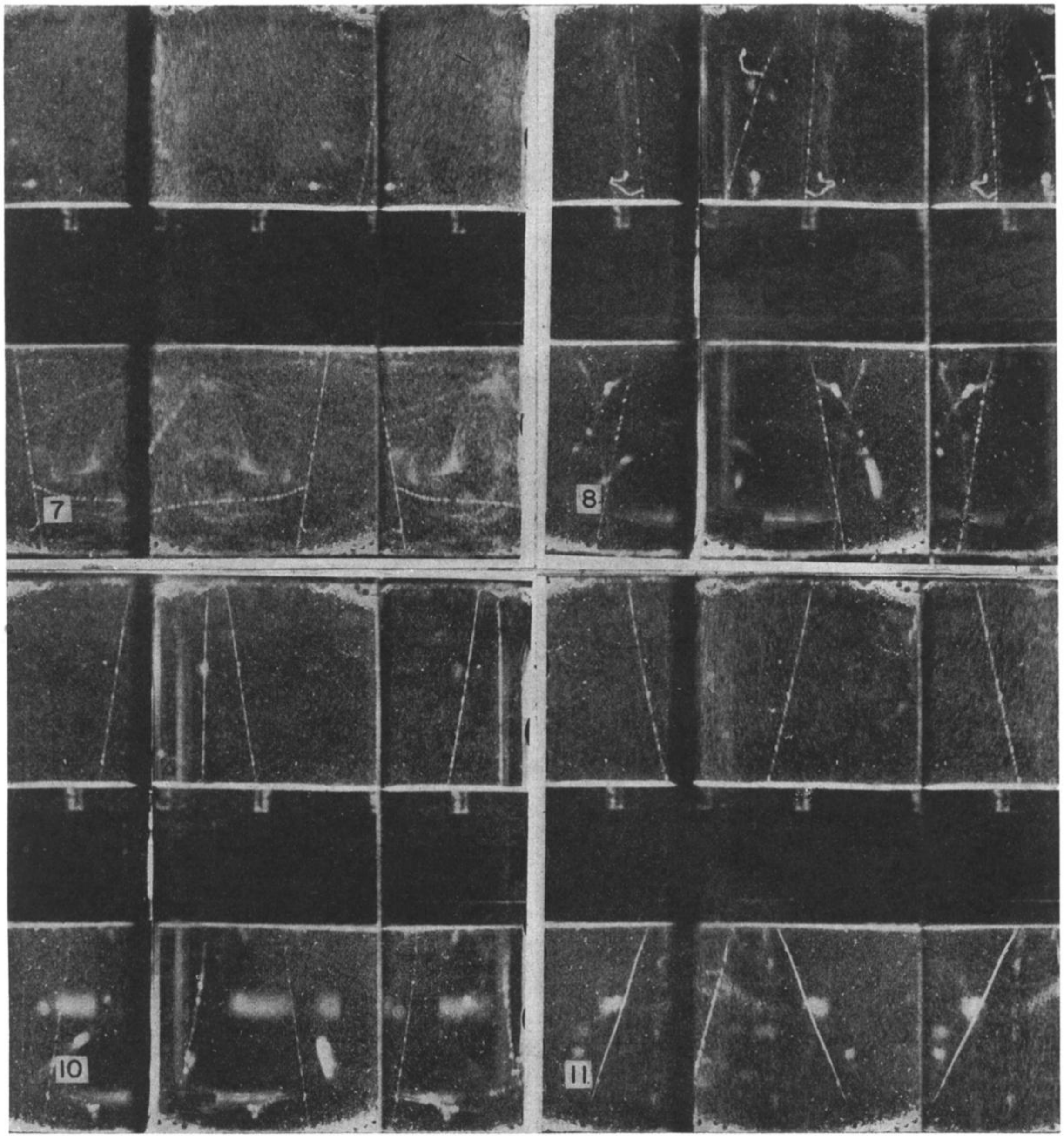
FIGS. 3–6.

FIG. 3. A meson penetrates 3.81 cm of tungsten and is accompanied by a collision electron. The central picture corresponds to a direct view while the two outer pictures are used for stereo comparison.

FIG. 4. A collision electron arising in the lead block above the cloud chamber accompanies the meson. The electron is stopped, but the meson penetrates the tungsten without multiplication.

FIG. 5. An electron shower of 5 particles accompanies the meson traversing the tungsten.

FIG. 6. Low energy collision electrons produced in the gas. Three such electrons arise from the meson track in the top half of the chamber.



FIGS. 7–8, 10–11.

FIG. 7. Two collision electrons arise from the meson track in the bottom half of the chamber. One electron passes out of view.

FIG. 8. Three collision electrons from a single meson. The meson produces a collision electron in the gas near the top of the tungsten plate, and penetrates the tungsten with a small deflection due to scattering. A collision electron also arises from the lead above the chamber and gives rise to a secondary collision electron in the gas near the top of the photograph.

FIG. 10. Shower of two mesons arising from the 7.62 cm Pb above the chamber penetrates the tungsten without multiplication. One of the tracks is slightly blurred in the botton half of the chamber due to motion of the gas.

FIG. 11. Possible nuclear disintegration arising in the tungsten. The penetrating particle shows very small scattering (2°) in the 3.81-cm tungsten plate. The heavily ionizing particle appears to arise in the center of the tungsten, and gives rise to two low energy collision electrons in the gas. These can be seen best in the right-hand picture.