SPECIFIC IONISATION OF COSMIC RAY PARTICLES.

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ABSTRACT.

An account of the cloud chamber investigation of the variation of total ionisation with energy for electrons, mesons and protons is given. The predicted relativistic rise of ionisation with energy when the kinetic energy is above the rest energy of the particle has been verified for electrons up to 5×10^8 e.v. For mesons there is an indication of the rise in ionisation with energy, but the amount of increase is lower than that predicted by the theory. Altogether 8 protons were observed in 5,000 photographs. Their specific ionisation is in satisfactory agreement with the theory.

INTRODUCTION.

According to Bloch (1933), Bhabha (1938) and others, the total ionisation produced by a charged particle per cm. of its path is given by:—

$$-\frac{dE}{dx} = 2\pi N Z r_0{}^2 \frac{mc^2}{\beta^2}\left[\log\frac{mc^2\beta^2 W_m}{(1-\beta^2)I^2Z^2}+(1-\beta^2)\right]$$

Here $N =$ No. of atoms per c.c. of the medium.

$Z =$ atomic number, $I(Z) =$ mean ionisation potential of the atom. Bloch put $I = 13{\cdot}5$ e.v.

$m =$ mass of the electron, $\beta = \frac{v}{c}$, $r_0 = \frac{e^2}{mc^2}$.

$M, E =$ mass and total energy respectively of the charged particle.

$$\gamma = \frac{E}{Mc^2}$$

$W_m =$ Maximum energy transferred to a secondary electron initially at rest.

According to Bhabha (1938)

$$W_m = \frac{2mM^2C^2(\gamma^2-1)}{m^2+M^2+2mM\gamma}.$$

Up to this time, this formula has not been experimentally verified over a wide range of energy of particles excepting by Corson and Brode (1938) who carried out measurements of total ionisation of Cosmic ray electrons lying within the energy range 1×10^6 e.v. and 3×10^7 e.v. by counting droplets on photographs taken with a counter controlled chamber. Their investigation, though of a preliminary nature, provides evidence that the ionisation reaches a minimum value for electrons of energy $1{\cdot}5 \times 10^6$ e.v., and beyond this minimum, ionisation increases roughly as predicted by the theory. Their observations, however, were restricted to relatively narrow range of energy and only to electronic component of Cosmic rays, and as such, left room for further investigations on the same line for electrons of higher energy and also for meson and proton components of Cosmic rays.

The total ionisation of Cosmic ray particles has been measured by the author in the energy range 2×10^6 e.v. to 3×10^9 e.v. This paper is concerned, firstly, with the experimental verification of the energy-ionisation relation for electrons up to ultra-relativistic region and, secondly, with the preliminary investigation of energy ionisation relation for mesons and protons.

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Experimental Method.

The present investigation was carried out by the cloud chamber method at the suggestion of Prof. Blackett in his laboratory during the years (1938–40). The apparatus was essentially the same as described by Blackett (1936), though many mechanical improvements were made. The improvement consists in making the chamber completely automatic to the extent that no attention was needed even during the long periods of operation. Three different fields were used in the investigation; 350 gauss for particles in energy range 1×10^6 e.v. to 1×10^7 e.v.; 2500 gauss for the range 1×10^7 e.v. to 3×10^8 e.v. and 8500 gauss for the range 3×10^8 e.v. to 3×10^9 e.v.

The chamber was enclosed in a copper box which helped to keep the temperature of the chamber as uniform as possible and thus reduced the track distortion. The gas mixture in the chamber was 90% argon and 10% oxygen and the condensant was 70% ethyl alcohol and 30% water.

In order to obtain sufficient diffusion of the track to enable the counting of the individual ions, a delay of the order of one-tenth of a second was introduced between the arrival of the particle and the expansion. This delay was controlled by the discharge of a condenser through a resistance.

The experimental arrangement was as follows: One camera placed at right angles to the chamber photographed the tracks for energy measurements, another camera placed at the side of the chamber took photographs of the same tracks by reflection on an aluminised glass mirror placed at $22\frac{1}{2}°$ to the axis of the chamber. By this method both the positive and the negative ions along the tracks, separated by an electric field between the front and the back of the chamber could be photographed and separately counted. Any loss of ions of one sign could thus be checked by comparing the number of ions per cm. in each branch of the track. Since the drops were photographed in the side camera by light scattered at 45° to the direction of incidence, the intensity of the scattered light was at least ten times the light scattered in the normal direction (Webb, 1935). Because of this gain in intensity, an aperture $f/6{\cdot}5$ could be used for the side camera, and the entire illuminated depth of the chamber could thus be brought into sharp focus.

Tracks of small curvatures were measured by the optical null method (Blackett, 1937) and those of larger curvatures were measured by the superposition of curves of known radii. For broad tracks, this method is superior to the usual practice of measuring co-ordinates, since it makes use of the whole photographic track as opposed to a finite number of points on it. The chamber distortion was determined by taking at regular intervals, throughout the experiment, photographs of tracks without the magnetic field. Measurements of twelve such tracks gave the mean curvature $c = 0{\cdot}4m^{-1}$. The mean curvature without field obtained by Blackett (1937) working with the same chamber with practically no delay was of the order $0{\cdot}05m^{-1}$. A decrease in delay would no doubt reduce the distortion and increase the maximum detectable energy but it would also reduce the diffusion of the track which is essential for counting droplets along the tracks. A compromise was thus necessary, and a delay of the order of one-tenth of a second was found to be most suitable.

Results and Discussions.

In 5,000 photographs taken altogether, there were 112 electron tracks in which both energy and ionisation were measurable. About a 100 meson tracks were also selected out of them for similar measurements. In all, only eight proton tracks were photographed, of which six could be used for ionisation measurements. The classification of the tracks were made in the following way:—

1. In general, all shower particles were assumed to be electrons with the exception of a few particles of energy 10^8 e.v., which were considered to be mesons responsible for the production of 'knock on' showers (Bhabha, 1938). It is clear that only one particle in a shower can be a meson. Three such particles were neglected in 40 measured showers on the ground that their ionisation and energy were consistent with their being mesons.

2. Single particles with energies less than 40×10^6 e.v. not exhibiting abnormally large ionisation were taken as electrons.

3. Single particles in the energy region 2×10^8 e.v. to 7×10^8 e.v. showing heavy ionisation were taken to be protons.

4. All other single particles were taken as mesons.

Finally all the tracks were divided into eight energy groups and the mean ionisation in each group was estimated by taking the average of the mean ionisation per cm. of each individual track in the group. The numerical results of all observations are summarised in the following table:—

Energy range in e-volts.	Mean ionisation per cm. of the track at N.T.P.					
	Electron.		Meson.		Proton.	
	Theoretical.	Experimental.	Theoretical.	Experimental.	Theoretical.	Experimental.
1×10^6—5×10^6	36	$38{\cdot}0 \pm 0{\cdot}7$	..	..	..	..
5×10^6—1×10^7	40·5	$42{\cdot}5 \pm 0{\cdot}6$	..	..	..	..
1×10^7—5×10^7	46	$48{\cdot}5 \pm 0{\cdot}6$	..	..	..	..
5×10^7—1×10^8	53	$54{\cdot}5 \pm 0{\cdot}8$	..	..	..	..
1×10^8—5×10^8	56	$56{\cdot}5 \pm 1{\cdot}5$	36	$41{\cdot}5 \pm {\cdot}6$	..	..
5×10^8—1×10^9	65	$63{\cdot}0 \pm 2{\cdot}1$	39	$41{\cdot}0 \pm {\cdot}6$	82	$77 \pm 1{\cdot}8$
1×10^9—3×10^9	..	..	41	$42{\cdot}5 \pm {\cdot}8$	..	..
Energy above: 3×10^9 ..	..	..	49	$47{\cdot}0 \pm {\cdot}5$	..	..

In order to compare the experimental results with the theory let us work out the ionisation for electrons, protons and mesons separately.

It is easily seen that

$$W_m = mc^2\gamma(\gamma-1) \quad \text{for electrons,}$$

$$= \frac{2mc^2(\gamma^2-1)}{1+\dfrac{2m\gamma}{M_p}} \quad \text{for protons, and}$$

$$= \frac{(\gamma^2-1)2mc^2}{1+\dfrac{2m\gamma}{M_m}+\dfrac{m^2}{M_m{}^2}} \quad \text{for mesons,}$$

where M_p = mass of the proton, and M_m = mass of the meson.

There is, however, some doubt as to whether Bhabha's theory of collision can apply to that between electron and electron, for, as we see from the above expression, if an electron with energy γmc^2 directly encounters a stationary electron, it gives the energy $(\gamma-1)mc^2$ to the latter and is itself reduced to rest. The total energy of the struck electron is now γmc^2, i.e. the rôles of the two electrons are reversed now. But one can easily see that such an event cannot take place, because most of the energy of the electron will be wasted in radiation. It is expected that the value of W_m when the ionising particle is an electron is much less than $(\gamma-1)mc^2$, but no lead on this point appears so far to have been given by theoretical workers on the subject.

It can now easily be shown that for the electron, the minimum ionisation is obtained for a value of γ which satisfied the equation

$$\frac{1}{(\gamma^2-1)^{\frac{1}{2}}}\left(4-\frac{1}{\gamma^2(1+\gamma^2)^{\frac{1}{2}}}\right)-\frac{2}{(\gamma^2-1)^{\frac{3}{2}}}\left\{\log\left(\frac{mc^2}{IZ}\right)^2+4\log(\gamma^2-1)^{\frac{1}{2}}-1-\log(\gamma+1)-\frac{(\gamma^2-)}{\gamma^3}\right\}=0.$$

This gives us $\gamma = 3{\cdot}5$, for $W_m = (\gamma-1)mc^2$ at energy of $1{\cdot}75 \times 10^6$ e.v. and the value of $-\frac{dE}{dx}$ comes out to be 61 ions per cm. The number of ions per cm. observed in the energy region 1×10^6 e.v. is, however, only $38 \pm {\cdot}7$. This discrepancy between the theoretical and experimental values is too large to be accounted for by the inaccuracy of the observation. This confirms our contention that W_m is not given by $(\gamma-1)mc^2$ at least in the case of the electron.

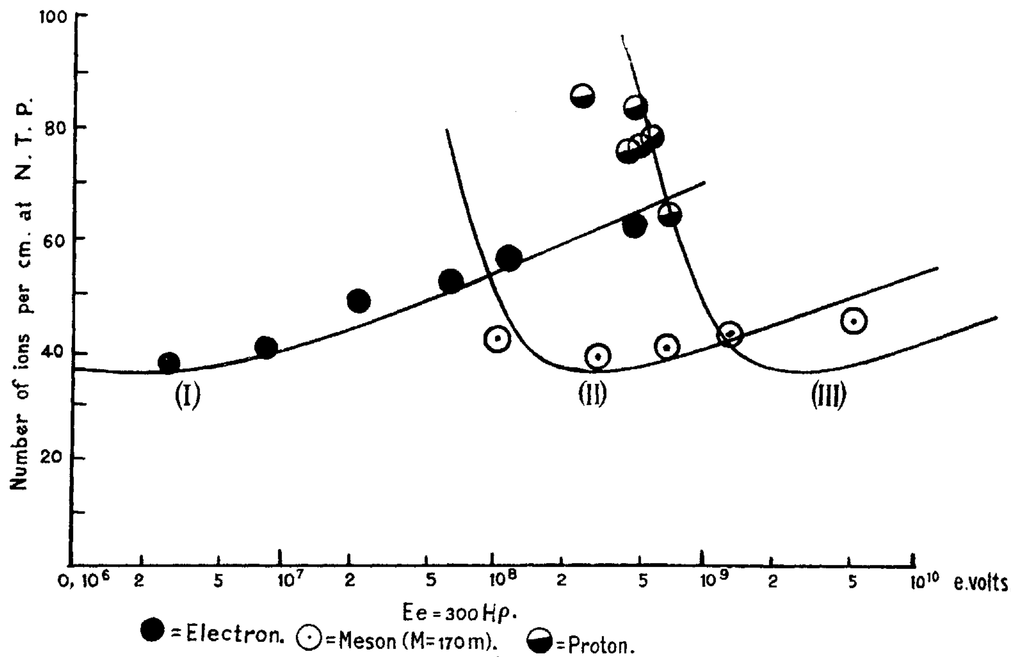

FIG. 1.

For mesons (mass $= 170m$.) and protons, $W_m \approx 2mc^2(\gamma-1)$ and $-\frac{dE}{dx}$ attains a minimum for a value of γ satisfying the relation

$$1-\log 2-\log \frac{mc^2}{IZ} -4\log \sqrt{\gamma^2-1}+2(\gamma^2-1) = 0$$

This equation is satisfied for $\gamma = 3{\cdot}2$, the corresponding energy being $2{\cdot}72 \times 10^8$ e.v. for mesons and $2{\cdot}944 \times 10^9$ e.v. for protons. For mesons the theoretical value of $-\frac{dE}{dx}$ corresponding to this energy comes out to be 68 ions per cm. (taking $33{\cdot}5$ e.v. = the energy used up per ion) against the experimental value of $41{\cdot}5 \pm {\cdot}6$ ions per cm. observed in the energy region between 1×10^8 e.v. to 5×10^8 e.v. We observe that in the case of electrons as well of mesons the agreement between the theoretical and experimental values of specific ionisation is far from being satisfactory. It is to be noted, however, that the region of energy determined experimentally, in which the minimum ionisation takes place, is rather flat (from $\gamma = 1{\cdot}17$ to $\gamma = 11{\cdot}7$) and coincides with the region of minimum ionisation determined by theoretical considerations.

For protons, only one point on the curve could be obtained and detailed comparison could not be made with the theory.

The expression $W_m = (\gamma - 1)mc^2$ for electrons is, therefore, not supported by the present experimental results. Either there is something wrong with the counting of particles, or the formula for ionisation requires modification.

As regards the second point, it is almost certain that we are not justified in putting the mean energy of ionisation $I(Z)$ where $I = 13{\cdot}54$ e.v., Z = atomic number. For nitrogen, it comes out to be about 95 volts. But the mean energy of ionisation is known to be 35 volts.

Putting $I(Z) = 35$ volts (Conduction of Electricity by Gases, by Thomson and Thomson, p. 103) in the expression for $-\frac{dE}{dx}$ in the case of mesons, and leaving W_m unaltered for the present, we find that for mesons the minimum value of $-\frac{dE}{dx}$ is obtained for $\gamma = 8{\cdot}8$, i.e. when $E = 7{\cdot}5 \times 10^8$. This is inside the flat region, but the value of $-\frac{dE}{dx}$ at this point is 86 ions. The agreement is therefore worse than before.

Another adjustment is possible if W_m is varied. It can easily be shown that for $I(Z) = 13{\cdot}5Z$ volts, we obtain the minimum observed value of 38 ions for electrons, if $W_m = 1187$ e.v., and minimum observed value of 41 ions for mesons, if $W_m = 1127$ e.v.

There is some evidence that the value of W_m is of the above order, for, if we look at the tracks carefully, we find that the number of particles along the track is not uniform throughout but some clusters are found at intervals. We may take these clusters as marking the points where the ionising particle imparts fairly large energy to the struck electrons, which produce large number of secondary electrons and thus lead to the formation of clusters. The maximum number of ions countable in a cluster, in the present experiment was 40, hence $40 \times 33{\cdot}5$ e.v. = 1340 e.v. is the maximum energy transferred to a secondary electron. If we identify this with W_m, the discrepancy between the theoretical and experimental values vanishes.

The theoretical energy ionisation curve for electrons has been drawn in Fig. 1, curve I, with this value of W_m. The shaded circles are the mean ionisation per cm. for electrons in different energy groups. The agreement of the experimental points with the theory is quite satisfactory up to 5×10^8 e.v. It is also seen that the specific ionisation of electrons of energy 5×10^8 e.v. is about 52% higher than that of a meson of the same energy, as is demanded by the theory. This agreement also gives a further evidence of the validity of the relativity theory up to ultra-relativistic region, as modified above.

The theoretical curve for mesons ($170m$) has been shown in Fig. 1, curve II. The open circles represent the mean observed ionisation at different energy intervals. The statistical error in each case is less than ± 1. The maximum detectable energy was 3×10^9 e.v. All the measured tracks above this energy were included in the last group, the mean energy being calculated on the assumption of $\frac{1}{E^3}$ spectrum.

Although the experimental value of specific ionisation of mesons at the first and last point is slightly lower than the theoretical value, there is a definite indication of the increase in ionisation with energy beyond 2×10^8 e.v. The chance that the observed increase is due to fluctuation is negligible. Since the higher energy tracks used for the determination of the last point on the meson curve may partly be due to protons, and since in this region protons ionise less than mesons, the actual ionisation for the mesons alone should be larger. A mixture of 10% proton and 90% meson would give rise to the observed deviation from the theoretical value.

In three thousand tracks photographed altogether, 8 heavy tracks of energy between 2×10^8 e.v. to 6×10^8 e.v. were observed all of which can be attributed to protons. The observed specific ionisation for protons has been plotted in Fig. 1, curve III, in half shaded circles. The experimental points do not show any large departure from the theoretical curve for protons. Large deviations from theoretical curve, however, are expected since the curve in this region is steep and the density of ions per cm. along the tracks reaches nearly the maximum number which could be counted. All the protons observed were of positive character; no deuteron or α-particle was observed.

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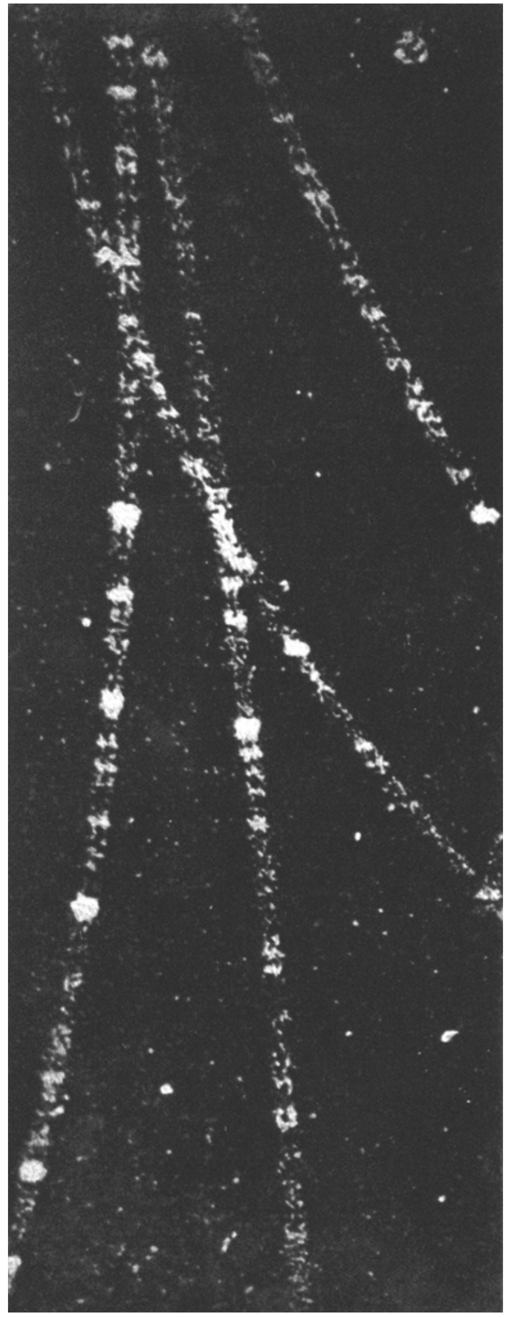

Photograph of a partially diffused shower taken with a magnetic field 8500 Gauss. The positive and negative ions along the tracks are just separated to be individually recognised. From energy and ionisation measurements one concludes that the least curved track in the group is a meson. The energy of the slowest particle in the shower is 1×10^7 e.v.

(The author regrets that the photographs of well diffused tracks suitable for accurate measurements which were actually used in this investigation are not available just at present and so could not be reproduced.)