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COSMIC RAYS AND MESOTRONS

By

H. J. J. BRADDICK

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H. J. J. BRADDICK, Ph.D.
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GENERAL EDITORS
M. L. E. OLIPHANT, PH.D., F.R.S.
Professor of Physics in the University of Birmingham
J. A. RATCLIFFE, M.A.
Lecturer in Physics in the University of Cambridge

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GENERAL PREFACE

It is the aim of these tracts to provide authoritative accounts of subjects of topical physical interest written by those actively engaged in research. Each author is encouraged to adopt an individualistic outlook and to write the tract from his own point of view without necessarily making it "complete" by the inclusion of references to all other workers or to all allied subjects; it is hoped that the tracts may present such surveys of subjects as the authors might give in a short course of specialised lectures.

By this means readers will be provided with accounts of those subjects which are advancing so rapidly that a full-length book would be out of place. From time to time it is hoped to issue new editions of tracts dealing with subjects in which the advance is more rapid.

M. L. O.
J. A. R.

AUTHOR'S PREFACE

During the last two years, the application of quantum theory to cosmic rays has made it possible to give a connected account of a large part of the phenomena. The theory of radiation from a moving electron has provided a satisfactory account of the behaviour of the less penetrating cosmic rays, and it is now clear that the more penetrating rays cannot be explained in terms of electrons. It has become necessary to introduce a new particle to account for these rays, and its properties are not yet fully explored.

In the present account, the first chapters are devoted to the experimental facts of cosmic rays, and the later to their explanation in terms of the properties predicted by quantum theory for moving charged particles.

The question of the *origin* of the rays has not been considered.

H. J. J. B.

January 1939

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Chapter I

INTRODUCTION

When a closed vessel is shielded as far as possible from the radioactive radiation of its surroundings, there is a residual production of about 2 ions per sec. per c.c. of air. The first definite evidence of the cosmic radiation was obtained by balloon flights which showed that this residual ionisation increased with altitude and might therefore be attributed to a penetrating radiation entering the earth's atmosphere from outer space (1). About 1926, Millikan and his collaborators took up the study of the rays, and made measurements of the absorption in air and water. Assuming that the radiation was electromagnetic and of γ-ray type, they interpreted their results on the basis of the then available formulae for X-ray absorption and assigned to the rays quantum energies of the order 10^8 electron-volts. D. Skobelzyn (2) found in a Wilson cloud chamber β-ray tracks whose energies, measured by their curvature in a magnetic field, went up to $1{\cdot}5 . 10^7$ e.v. Bothe and Kohlhörster (3) interposed a block of gold between two Geiger-Müller β-ray counters and showed by observing coincident discharges of the two counters that there were corpuscular rays whose penetrating power was of the same order as that measured for the cosmic radiation. This work suggested the possibility that the primary radiation was corpuscular, and Bothe and Kohlhörster pointed out that charged particles approaching the earth from outer space should be deflected by the earth's magnetic field. The field would prevent the less energetic particles from reaching equatorial regions, and give rise to a variation of cosmic-ray intensity increasing from the equator toward the poles. A variation of this kind was found by Clay and extensively explored by Compton. This latitude variation shows that a large part of the radiation consists of charged particles; the most recent calculations, based on high-altitude measurements in different latitudes, indicate that the rays reaching the top of the atmosphere are almost entirely corpuscular (4). When the rays enter the atmosphere there is a complicated process of absorption and secondary ray production, and it is to be emphasised that the deflection by the earth's magnetic field takes place outside the atmosphere and gives direct evidence about the primary incident particles.

The energy distribution of the particles which reach the earth's surface may be investigated by the curvature of the tracks in a strong magnetic field. The particles are found to have energies up to the limit observable at about $7 . 10^{10}$ e.v. There is indirect evidence that there exist particles of much greater energy than this. The tracks observed in the expansion chamber indicate particles of both signs, and these tracks in fact provided the first evidence for the positive electron (positron).

Amongst the interactions of cosmic particles with matter, a most characteristic phenomenon is the production of showers. In Skobelzyn's early cloud-chamber experiments there were a few observations of the simultaneous passage of several tracks through the chamber. Further work with the Wilson chamber, and with sets of Geiger counters, showed that showers of particles were found most frequently in the neighbourhood of heavy elements. In chamber photographs of typical showers, a number of tracks came from a limited region of the heavy element, or from a number of such centres. In experiments with ionisation chambers there had been found occasional bursts of ionisation, corresponding to the simultaneous production of 10^5–10^7 ion pairs. These "bursts" or "Stösse" were first thought to be a separate phenomenon, but it now seems probable that most of them are very large showers of the type described above. Recently, the theoretical importance of the showers has become evident, for it appears that the quantum theory, if applied to electrons and γ-rays of very high energy, in a region where its validity was formerly uncertain, predicts the production of showers by a cascade process.

Some of the cosmic particles, primary or secondary, have very great penetrating power, for cosmic rays can be detected, not only at the bottom of the normal atmosphere, but under great depths of water and in deep mines. Absorption measurements show that the radiation at sea level can be split rather definitely into a more absorbable and a less absorbable component. The more absorbable component may be satisfactorily interpreted as consisting of electrons and photons, which lose energy according to quantum theory. The hard component is very much more penetrating. It is likely that the hard component consists of particles with hitherto unknown properties, and there is a considerable body of evidence that they have a mass intermediate between the electron and the proton masses. It appears probable that these particles are secondary to incoming electrons, rather than primary particles from outside.

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Chapter II

METHODS OF INVESTIGATION

2·1. In modern cosmic-ray investigations the main methods used are:

(1) The ionisation chamber in which the ionisation current is measured by an electroscope or electrometer.

(2) Systems of Geiger-Müller counters.

(3) The cloud chamber of C. T. R. Wilson.

As a special method may be mentioned the photographic emulsion technique of Blau, in which the tracks of an ionising particle are observed by the lines of blackened grains left in a photographic emulsion. This method has been applied to the discovery of rare disintegrations producing particles of mass comparable with α-particles or protons.

2·2. The ionisation chamber.

An ionisation chamber for cosmic-ray measurement is usually filled with gas under pressure; an electric field is applied to drive the ions to a collecting electrode, and the ionisation current is measured by some form of electrometer. Some of the ions are lost by recombination before they are collected. This loss depends on the collecting electric field, the pressure and nature of the gas, and the distribution of the ionisation about the electrode system. The loss by recombination is larger for a heavily ionising particle than for an electron, and the variation of ionisation with pressure has been used to provide evidence that the particles in bursts ionise like electrons.

Recombination is less marked in pure argon than in most other gases, and the specific ionisation along an electron track is large in this gas. It is therefore often used in cosmic-ray measuring chambers. The ionisation chamber is valuable in accurate comparisons of cosmic-ray intensity, since the measuring arrangement has stable characteristics and the calibration may be checked with a radioactive source. It may be used in the study of the geographical and time variations of the intensity.

In the form of a light electroscope carried by balloons, the ionisation chamber has been used for investigating the change of cosmic-ray intensity with altitude. In the interpretation of these results, however, there is a complication due to the fact that rays are incident at all angles and reach the instrument through different thicknesses of air. The theoretical investigations of the passage of rays through absorbing layers lead naturally to an absorption curve for unidirectional radiation. Such a curve is obtained directly by a vertical counter arrangement, but Gross (1) has shown that it may be obtained from ionisation-chamber measurements by the transformation

$$\psi(x) = J(x) - x\frac{dJ(x)}{dx},$$

where x = depth of penetration,

$J(x)$ = observed intensity (all directions),

$\psi(x)$ = computed intensity of a normally incident beam.

In deducing this formula it is assumed that the initial rays enter isotropically over a hemisphere and that the absorption and secondary production of a particular ray is confined to a single line, i.e. that there is no sideways scattering.

2·3. Superimposed on the steady ionisation current in an ionisation chamber there are bursts of ions due to the simultaneous passage of a number of ionising rays. These may be measured by a recording electrometer or by a valve amplifier which responds to the sudden increase in ionisation current. The lower limit to the size of a detectable burst is set by fluctuations in the ordinary ionisation current due to unrelated cosmic rays arriving at random times. If a number of such rays happen to pass in a time comparable with the time of collection of the ions, or the time of response of the recorder, a spurious burst will be recorded. In the case of an ionisation chamber connected to a valve amplifier it is usually the time of collection of ions which must be considered in this connection; when an electrometer is used it is frequently the time of swing of the moving needle. Formulae for calculating the number of spurious bursts due to fluctuations may be obtained (2). For the case where the average number of particles arriving in a time equal to the "time of resolution" is small compared with the least number of simultaneous particles counted as a burst, the number of spurious bursts is given by an approximate formula:

$$P = \frac{1}{T}\sqrt{\frac{n}{2\pi}}\,e^{-k^2/2n},$$

where P = number of "spurious bursts" with more than k particles,

m = average number of random particles per second,

T = time of resolution,

$n = mT$

$k \gg n$.

In the case of a small chamber used by R. T. Young (3), which may be taken as typical, bursts of ten rays could be recorded, and the number of spurious bursts of this size, due to fluctuations, was negligible.

2·4. The Geiger-Müller counter.

The Geiger-Müller counter usually takes the form of a tubular cathode and a fine wire anode sealed up in a tube containing gas at low pressure. If the voltage applied to the counter lies within certain limits, the ionisation produced by the passage of a particle through the counting tube is magnified by collision and other processes within the counter itself. Each particle gives rise to a short quenched discharge, which ordinarily lasts for about 10^{-2} sec. This time may be reduced by the use of special quenching circuits. A counter tube responds to the passage of cosmic-ray particles, but it also responds to radioactive contamination and most tubes probably give also spontaneous discharges. There are a number of circuits which record only the coincident discharges of a number of counters (4)—discharges being coincident if they occur within a certain time called the resolving time of the apparatus. In practice, with simple circuits, this time is of the order 10^{-3} sec., and it can be reduced by the use of special circuits. The resolving time can be made less than the duration of a single counter impulse because the amplifying circuits can be adjusted to respond only to the initial, steeply rising, part of the impulse. Local radioactivity does not give rise to genuine coincidences, since radioactive β particles cannot in general penetrate more than one counter, but there are apparent coincidences due to the random passage of a particle in each of the counters within the resolving time. The number of these casual "coincidences" in unit time is given in the case of two counters by

$$A_{12} = 2N_1 N_2 \tau,$$

where $N_1 N_2$ = average numbers of random impulses in the counters in unit time,

τ = resolving time.

The corresponding approximate formula for the case of three counters is

$$6N_1 N_2 N_3 \tau^2.$$

The number of casual coincidences in practical cases decreases very rapidly with an increase in the number of counters.

In the simplest use of the coincidence system, two or more tubular counters are arranged with their axes parallel (Fig. 2·1 *a*). The passage of a single particle through all the counters produces a count, and the arrangement may be used as a "telescope" to distinguish rays coming from a particular direction. A set of counters arranged in this way may be used to measure the absorption of the rays, the blocks of absorbing material being interposed between the counters (§ 4·3).

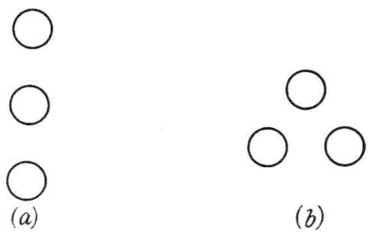

Fig. 2·1.

The method of coincidence counting has been extended to the observation of more complicated events. The arrangement of counters shown in Fig. 2·1 *b* responds only if at least two particles pass simultaneously, and it is typical of a number of arrangements used in the investigation of showers.

2·5. The Wilson cloud chamber.

In the cloud chamber, the tracks of ionisation left by individual particles are made visible by the condensation of liquid drops on the ions as nuclei.

The uses of the cloud chamber in cosmic-ray research are of three main types:

(1) The chamber may be used to show the general nature of the phenomena and for the statistical study of some special phenomenon such as shower production.

(2) The chamber may be used in a magnetic field and the curvature of the tracks measured. This allows a direct deduction of the energy of the particles, for we have

$$H\rho = \frac{m}{e}\frac{\beta c}{\sqrt{1-\beta^2}},$$

$$10^8 V = \frac{mc^2}{e}\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right),$$

where H = magnetic field (gauss),

ρ = radius of curvature,

V = energy in electron-volts,

$\beta = \frac{v}{c}$,

v = velocity of particle,

c = velocity of light.

When the energy of the particle is very large compared with mc^2, we have

$$V = H\rho\frac{c}{10^8} = 300H\rho,$$

and the mass of the particle does not appear in the expression.

For a particle of energy 10^9 e.v. and a field of 10,000 gauss, the radius of curvature is 3 metres, so that refined curvature measurements are necessary to measure the energy of fast particles. In particular the distortion of the tracks, due to irregular motion of the air in the chamber, must be reduced to a minimum. At the present level of technique, the energy of a particle of 10^9 e.v. can be measured to about 5 per cent and the curvature can just be detected for a particle of energy $7 \cdot 10^{10}$ e.v.

(3) The chamber photographs may be used to find the density of ionisation along the track (the "specific ionisation"). It will be shown (§ 6·2) that in a certain energy range the density of ionisation of a particle of given energy depends on the mass of the particle. Measurement of the specific ionisation and the curvature of the track of a particle in this range enables its mass to be determined. For the purpose of determining the ionisation the chamber conditions may be set to give diffuse tracks in which individual droplets, corresponding to single ions, can be counted.

Cosmic-ray tracks were first found in chamber photographs taken for a different investigation, and the expansions were made at random times as far as cosmic rays were concerned. The probability of finding a cosmic-ray track in a random expansion depends on the time during which the gas in the chamber is in a condition to deposit droplets on ions. The considerations affecting this will be discussed below. With a chamber of ordinary design, Anderson obtained one track in about five expansions, but only a small proportion of these were suitable for detailed study. Blackett and Occhialini (5) introduced a technique for making the passage of the ray take its own photograph, the expansion being initiated by the simultaneous discharge of Geiger counters fixed above and below the chamber. This method gives a large yield of tracks which are suitable for accurate curvature measurement, but it must be remembered that the events photographed are selected according to the probability of their tripping the counters. Showers, for example, occur more frequently than in random expansions, and particles which come