

"THE EAST WEST ASYMMETRY OF
COSMIC RAYS IN HIGH LATITUDES"

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PREFACE

The experimental work described in this thesis was carried out with the subject of obtaining information on the east-west asymmetry of cosmic rays in latitudes above the so called knee of the latitude intensity variation of the total cosmic ray intensity. As is explained in the Introduction, the variation of intensity with latitude and the east-west asymmetry observed between the geomagnetic equator and the latitude of the knee (about 45° geomagnetic) can be explained in terms of the effect on the primary radiation of the earth's magnetic field. At higher latitudes where little or no variation of the intensity with latitude has been found, the east-west asymmetry should vanish according to this theory. A small asymmetry has however been found by various workers, notably T.H. Johnson and F.G.P. Seidl, in latitudes above the knee. Johnson (1941) has given a theory to account for this as an effect produced by the deflection of secondary cosmic ray particles in the earth's field. The values of the asymmetry calculated by Johnson for various zenith angles were compared with results obtained at 49° and 54° north geomagnetic latitude.

Owing to the large probable errors of the experimental results, no more than a very general conclusion could be drawn from the comparison. The geomagnetic latitude of Hobart, 51.7°S , made it a suitable place to obtain results to supplement those of Seidl and Johnson, and the Hobart experiments were planned with the aim of improving the statistical precision of the results to a point where they could be used as the basis of a critical test of Johnson's theory. In the later sections of this thesis the theory is discussed in some detail. The values of the asymmetry which might be expected have been recalculated, using more recent data than that available to Johnson, graphical and numerical methods being substituted for analytical methods in some parts of the calculations in order to use empirical data directly.

It is important to establish as definitely as possible that the deflection of secondary cosmic rays between the top of the atmosphere where they are produced and sea level can lead to an asymmetry because of the apparent contradiction which the asymmetry observed in high latitudes presents to the general theory which has been found to explain the geomagnetic effects in a satisfactory manner. By showing that Johnson's, or a similar theory can adequately explain this phenomenon, the contradiction

can be removed.

The history of the experimental work on this problem is as follows. In 1946, Dr. A.G. Fenton commenced work on the construction of an automatic apparatus using a single geiger counter telescope pointing east and west alternately to measure the asymmetry. The author assisted with this work, and in 1947 when Dr. Fenton was absent on leave from the laboratory, completed the apparatus and operated it successfully to obtain results which were published in the Physical Review (Vol. 74, 589, 1948). While this setup was in operation it was decided to construct an apparatus using two geiger counter telescopes instead of one. The advantages of such an arrangement are discussed in the section in which this apparatus is described. The design and operation of this setup was almost entirely the work of the author. It was operated from the end of June 1948 until the beginning of August, 1949.

At the end of 1948 the Australian National Antarctic Research Expedition became interested in the investigation of the asymmetry and made a grant of money to enable Dr. Fenton's brother, Mr. K.B. Fenton, to extend the work to geomagnetic latitude 60.7°S by operating an apparatus similar to the Hobart one on Macquarie Island in 1950 and possibly 1951.

iv.

Problems incident to the operation of apparatus remote from the facilities available in the laboratory made the construction of this apparatus a project of considerable magnitude, and it was accordingly shared between Dr. Fenton, his brother, and the author. Dr. Fenton who had worked on the properties of geiger counters in Birmingham undertook to construct the counters required, while his brother took responsibility for the design and construction of suitable recording circuits. The contributions of the author to this work are described in Part II, and included the design of an automatic 35mm. camera to record the results, the modification of a turntable previously used in a Predictor unit to make it suitable for mounting of the apparatus, and the design of control gear to make the setup automatic in operation. The construction of this apparatus was successfully completed in time for it to be shipped to Macquarie Island in April, 1950.

Between April and June, 1950, the Hobart apparatus was modified to include several improvements. The most important of these was the fitting of larger trays of geiger counters to increase the counting rates, which was possible because of the improved supply of counters available at that time. The modifications were completed by the time the Macquarie Island gear was ready for use, and the two sets were put into operation on parallel schedules at the end of June, 1950.

The author's work which is the subject of this thesis begins with the construction of the first double telescope apparatus and includes the results obtained up to the end of 1950.

The author wishes to acknowledge gratefully the financial assistance given by the Commonwealth Scientific and Industrial Research Organisation which made this work possible. Unpublished results kindly made available from Macquarie Island by Mr. K.B. Fenton have been used for comparison with those obtained at Hobart by courtesy of the Australian National Antarctic Research Expedition. Professor A.L. McAulay by encouragement and advice has at all times helped to forward the investigations, and Dr. Fenton has contributed much in discussion and assistance at various stages of the work. To these and other members of the laboratory staff who have co-operated with the author at different times, grateful acknowledgement is made.

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INTRODUCTION.

The world wide survey of cosmic ray intensity carried out by various workers (Compton, 1932a, 1932b, 1933; Compton et al. 1934; Bennett et al. 1932; and others) showed that the variation in cosmic ray intensity at sea level follows geomagnetic latitude and longitude rather than geographic latitude and longitude or lines of equal declination.¹ This supported the idea that the primary cosmic rays consist mostly of electrically charged material particles which undergo deflection in the dipole field of the earth. It was shown by G. Lemaitre and M.S. Vallarta (1932) that the variation in the intensity found experimentally could be fully accounted for by considering the influence of the earth's magnetic field on a primary radiation consisting of charged particles coming to the earth from all directions in space.

The experimental results showed a minimum intensity at the geomagnetic equator and an increase up to geomagnetic latitudes of about 45° - 50° north or south, then a constant intensity from there towards the poles.

1. The geomagnetic latitude is not to be confused with the magnetic latitude μ defined by $\tan \mu = \frac{1}{2} \tan \delta$, where δ is the local value of the magnetic dip. The magnetic latitude is controlled by local anomalies, whereas the geomagnetic latitude depends on the orientation of the assumed dipole. The geomagnetic latitude is given by

$$\sin \lambda = \cos 78.5^{\circ} \cos (\Lambda - 69.0^{\circ}) \cos \Omega + \sin 78.5^{\circ} \sin \Omega$$

where Λ is the geographic latitude and Ω the west geographic longitude.

The graph of intensity against latitude is shown in Figure 1. The part of the curve where the flattening out occurs has come to be referred to as the "knee" (this term will be used frequently in the text), and the latitudes on the equator and pole sides of the knee are often referred to as low and high latitudes respectively when discussing cosmic ray effects.

Very little if any dependence of the latitude of the knee on the altitude at which measurements are made has been found, although the amount by which the intensity varies between the geomagnetic equator and the knee does depend on the altitude. A comparison between measurements of the variation of intensity with altitude made by Pfozter (1936) in geomagnetic latitude 49°N with those made by Carmichael and Dymond (1939) at 88°N geomagnetic latitude show very little difference between the intensity at the two latitudes for any altitude (See Montgomery, 1949, p. 158). From this it can be concluded that the latitude effect extends to the same latitude at all altitudes.

Bruno Rossi (1930) showed that if particles of one sign charge predominate in the primary radiation then the deflections that they undergo in the earth's field should result in an east west asymmetry in the radiation, that is the intensity at an angle θ to the west of the vertical should be greater than

that at an angle θ to the east of the vertical if the primary particles are predominantly positive, and less if they are predominantly negative. Johnson and Street (1933) using a triple coincidence counter telescope found a definite though small difference between the east and west intensities at an altitude of 6288 feet in geomagnetic latitude 51°N , the smaller intensity being in the east. Following this, a number of workers obtained results in different latitudes which definitely established that the intensity of the radiation coming from the west is greater than that from the east. These results are summarised in a review by Johnson (1938), and they show that the asymmetry is greatest at the geomagnetic equator and decreases in going towards higher latitudes.

$$\text{The quantity} \\ \alpha = \frac{(j_w - j_e)}{\frac{1}{2}(j_w + j_e)}$$

which is used as a measure of the east west asymmetry is 0.15 for the zenith angle of 45° at $\lambda = 0$ and decreases to about 0.02 or less at $\lambda = 50^{\circ}$.

It is interesting to see the general argument by which the experimental data on the latitude effect and the east west asymmetry are connected with the theory of the orbits of the primary cosmic rays in the earth's magnetic field. This is given in outline in the next sections. Only the main points of the argument

are given, as the details can be found elsewhere and are not necessary for an understanding of the background of the high latitude asymmetry. Convenient summaries of the theory of the primary orbits are given by Montgomery (1949) and Janossy (1948) who also give references to the original work.

The theory of the orbits of the primary cosmic ray particles tells whether or not a particle of given energy, mass and charge can reach the top of the atmosphere in a given direction along a trajectory starting at a great distance from the earth. Depending on the geomagnetic latitude, to a smaller extent the longitude, and the energy of the particles, there are three alternatives.

- a. The particles can approach from any direction.
- b.. The particles cannot reach the top of the atmosphere from any direction at all.
- c. Some directions of approach are "allowed," others are forbidden.

In the third case to a sufficiently good approximation for the present discussion the allowed directions cover a region of the sky bounded by a cone called the "allowed cone."¹ The axis of the allowed cones points to the west for positive and the east for negative particles.

An application of a form of Liouville's theorem (Lemaitre and Vallarta, 1933; Swann 1933) to the motion of the primary particles gives the result that if it be assumed that the intensity of particles which all have the same energy, mass and charge is isotropic at infinity, then the intensity of the particles at the top of the atmosphere will be the same in all allowed directions and equal to the intensity at infinity, and zero in all forbidden directions. This means that the contribution of particles of a certain energy to the omnidirectional intensity² at any particular place is proportional to the solid angle

1. The Stormer theory gives a circular allowed cone. While all directions outside this are forbidden, not all directions within it are allowed due to shadow effects of the solid earth. Vallarta (see Janossy, 1948, p.282 for summary) defined a "main cone" which lies within the Stormer cone, and all directions within the main cone are allowed. Further a region called the simple shadow cone can be delimited, and outside this cone all directions are forbidden. Between the simple shadow cone and the main cone is a region called the penumbra. The penumbra is a complex region containing an infinite number of allowed and forbidden subregions. The use of the simple allowed cone is sufficient to show the form of the theory for the explanation of the latitude and east-west effects.

2. The intensity as measured by, for example, a spherical ionisation chamber.

of the allowed cone, and that they contribute to the intensity measured in a certain direction¹ only if that direction is included in the allowed cone.

The effect of the earth's magnetic field on the primary orbits is greatest at the geomagnetic equator, and it is here that the intensity is found to be a minimum and the east west effect greatest. To a place of geomagnetic latitude λ correspond two critical energies, $E_1(\lambda)$ and $E_2(\lambda)$. Particles of energy greater than $E_1(\lambda)$ can arrive from any direction, and particles of energy less than $E_2(\lambda)$ cannot reach the place at all. Those with intermediate energies can arrive from some directions but not from others, that is their allowed cones cover only part of the sky. These critical energies are greatest at the geomagnetic equator and decrease as λ increases. Thus in going from the equator to higher latitudes more and more energies are included in the range with which particles can reach the earth's surface as the allowed cones open up, those for positive particles from the west, those for negative particles from the east. Since the energies of the primary particles are spread over a spectrum, more particles are able to contribute

1. The intensity as measured by a geiger counter telescope.

to the radiation and hence the change in intensity with latitude. Since the positive primaries in the energy range (E_1, E_2) contribute more to the radiation from the west and the negative particles in this range contribute more to the radiation from the east, any unbalance in the intensity of the positive and negative particles gives rise to an east west asymmetry. The observed western excess indicates an excess of positive particles in the primary radiation.

Consider in the light of the foregoing analysis the fact that the change of intensity ceases at the knee of the latitude effect and is constant from there to the poles. This indicates a cutoff of the energy spectrum of the primary radiation at the energy whose allowed cone just covers the whole upper hemisphere at the latitude of the knee ($E_1(\lambda_{\text{knee}})$). It was at first thought that this could be due to the absorption in the atmosphere of any radiation caused by primaries with energy less than the cutoff. This could explain the occurrence of the knee at sea level, but the radiation caused by the low energy primaries would penetrate to altitudes above sea level before being absorbed and at high altitudes the position of the knee would be different. The fact that the latitude of the knee is independent of altitude therefore is incompatible with this explanation. The alternative is to assume

that the absence of primaries below the cutoff energy is due to some cause which affects the primary radiation before it reaches the atmosphere. A discussion of various theories which have been advanced to account for this low energy cutoff has recently been given by Gething (1950).

All the primary cosmic ray particles must be able to reach the top of the atmosphere from any direction at latitudes above the knee, for if there were any whose allowed cones did not cover the whole sky at the latitude of the knee, these allowed cones would increase in going to higher latitudes and the result would be a change in intensity, contrary to observation. Therefore at latitudes above the knee, any pair of directions at equal angles with the vertical in the east and west will be allowed directions for any primary particles, and the primary radiation will contribute equally to the intensity in these two directions. The east west asymmetry of the primary radiation should therefore become zero at the latitude where the variation of total intensity with latitude ceases.

Contrary to the conclusion reached in the previous section a small east west asymmetry has been found in latitudes above the knee, which is generally agreed to lie below geomagnetic latitude 50° . Johnson and Street (1933) observed a small asymmetry in geomagnetic latitude 56°N at an elevation of 6,288 ft. In geomagnetic latitude 51°N , Johnson and Stevenson (1933) found that the west intensity was 3 per cent higher than the east at 30° from the vertical. Stearns and Froman (1934) found a definite asymmetry at geomagnetic latitude of 49° . Johnson (1935 and 1938) has summarised the results of these and other workers. More recently Seidl (1941) has reported a definite asymmetry at 20° from the vertical in geomagnetic latitude 54°N .

If the theory outlined above be accepted, and there is good reason for this because of the satisfactory way in which it explains the latitude effect and the east-west asymmetry in low latitudes, it is necessary to regard the asymmetry observed above the knee as an effect pertaining to the secondary radiation. Johnson (1941) calculated the asymmetry which would be expected to arise because the secondary mesons which make up the penetrating component of the radiation at sea level are deflected by the earth's magnetic field during their flight through the atmosphere. He was able to account for an asymmetry of the same order of magnitude as that observed.

A copy of Johnson's paper is attached, and should be referred to for details. The calculation of the asymmetry will be discussed fully in a later section.

Owing to the large probable errors of the experimental results with which Johnson compared his predicted values of the asymmetry, it was not possible to say definitely whether his theory really did give an adequate description of the east west effect in high latitudes. The experiments which have been conducted in Hobart were designed to improve the statistical precision of the measured asymmetry, and so provide a basis on which Johnson's theory might be critically analysed. The situation of Hobart in 51.7° south geomagnetic latitude made it a suitable place to obtain results to supplement those obtained by Johnson (1941) and Seidl (1941) in north geomagnetic latitudes of 54° and 49° respectively. The results of Caro, Law, and Rathgeber (1948) who found no variation in the total intensity between Melbourne (some 5° north of Hobart) and geomagnetic latitude 84° S place Hobart well above the knee.

A pair of double coincidence geiger counter telescopes which will be described later have been used for the determination of the asymmetry at Hobart. At zenith angle settings of 15, 30, 45 and 60° measurements have been made with 12 centimetres of lead between the counter trays, while at 45 and 60°

experiments have also been made with no lead and 25 centimetres of lead. Results are available for comparison from Macquarie Island, 60.7° south geomagnetic latitude.

In a later section the theory of the asymmetry will be discussed in some detail. The predicted values are in good agreement with those found for small zenith angles where the subsidiary data used in the calculations such as the energy spectrum and the positive excess of the mesons are well known. The agreement at 45° and 60° from the vertical is not so good, although data used for the calculation of the asymmetry at these angles is not as reliable as that used for the smaller zenith angles.

The Macquarie Island results show a smaller though definite asymmetry than is found at Hobart. Since Macquarie Island is at least 10° above the accepted position of the knee this may be taken as very strong support for the idea that the asymmetry is a secondary radiation effect in these latitudes.

THE DESIGN AND CONSTRUCTION OF THE FIRST DOUBLE
TELESCOPE APPARATUS.

An account of the first measurements of the east west asymmetry made at Hobart has already been published (Fenton and Burbury, 1948). These early experiments were made with a single geiger counter telescope which was pointed to the east and west alternately, and the east and west intensities were computed by dividing the total number of counts recorded in each direction by the total time for which the telescope was pointing in each direction. Useful data was obtained with this apparatus which was operated automatically during late 1947 and early 1948. During the time when the single telescope was being used an improved apparatus using two telescopes was planned. It was reasoned that two telescopes pointing to the east and west at the same time would have several advantages over a single telescope in obtaining a good estimate of the asymmetry.

The results obtained with a double telescope apparatus would be less influenced by short term variations in the cosmic ray intensity than those from a single telescope. For example, if a sudden erratic increase in the total intensity

such as might be associated with a magnetic disturbance occurred when the apparatus was pointing east it would make the east rate appear higher. With the double telescope however both the east and the west rates would be affected. Another advantage in using the two telescopes would be that the number of counts necessary to achieve the statistical accuracy required would be obtained in a shorter time.

As well as the general advantages of a double telescope apparatus mentioned above there were improvements suggested by the experience gained on the single telescope apparatus, the most important of these being in connection with the timer unit which controlled the automatic operation of the gear. As described previously (1948) the results were recorded by a 16 mm. camera controlled by the timer which also changed the setting of the telescope from east to west or vice versa. A photograph of the clock, a mechanical recorder which registered the number of particles counted, and an indicator to show which way the telescope was pointing was taken at the beginning and end of each run. From the data obtained the number of counts recorded in each run and the length

of each run could be found. The basis of the timer used was a small synchronous motor of the shaded pole continuous armature type which, although fairly good as a timekeeper, showed an appreciable tendency to change its speed from time to time, probably as its load changed with changing ambient temperature and it would be found when reading the results from the film that the periods for which the apparatus was at one setting would vary in length by up to several minutes. This meant reading the time to the nearest second from every photograph to determine the intervals exactly, and the effect of fatigue was found to be a source of error in this. After reading results from a film for half an hour or so the concentration of the reader would fall off and errors, such as confusing 5 and 10 past, 20 and 25 past, etc., and taking the reading of the minute hand to the nearest minute graduation rather than the one last past would be committed. Reading the films and making sure they were read correctly was very tedious, and it was decided that the work required to improve the timing unit to a point where it would give runs of equal length, preferably multiples of an hour, would be well justified for this reason.

Also, statistical analysis of the results would be simplified as counting rates recorded in equal runs would have equal statistical weight, and the saving of computation in dealing with a large number of results would be considerable.

At the commencement of the construction of the double telescope apparatus, then, the task appeared to consist of

- (a) the construction of two geiger counter telescopes and recording circuits similar to that already in use;
- (b) the construction of an improved timer to control the automatic operation of the apparatus and give exactly equal intervals of recording time.

The construction of the new apparatus and getting it to operate satisfactorily did not prove to be as simple as this, for in running the two sets of recording circuits side by side the problem of interference was found to present difficulties. The manner in which these were overcome will be described later under the sections describing those parts of the circuit which were affected.

Figure 2 shows the layout of the double telescope apparatus in the form of a block diagram. The various components will be described separately, first the cosmic ray detecting and recording section, then

the timing mechanism controlling the automatic operation of the apparatus.

THE GEIGER COUNTER TELESCOPES AND SUPPORTS.

The telescopes each consisted of two banks of geiger counters connected to a coincidence circuit, and mounted in cast aluminium frames. The frames were supported in cast iron yokes bolted to a steel plate on top of the turntable. The turntable was supported on ball bearings in a cast iron tripod supported by three levelling screws from a steel plate firmly bolted to a 2' x 2' concrete block, the rotation of the turntable being effected by a reversible electric motor driving the turntable shaft through a double worm reduction gear and belt drive.

The belt drive was adjusted to have a certain amount of slip so that any sudden starting or stopping of the motor or the turntable would not strain the driving mechanism. Stops were fitted to the periphery of the turntable to establish the azimuth settings of the apparatus by resting against the pole of an electromagnet. The electric motor was controlled by switchgear which will be described in connection with the timing gear.

Steel pins through bosses in the side plates and holes in the supporting yokes formed a pivot on which the telescopes could be turned to obtain the zenith angle settings, and by tightening a nut on the end of the pins they could be clamped in place. A steel grid was fitted to the underside of each telescope frame to support lead plates between the counter trays.

Six geiger counters were used for each telescope, three in each of the two banks comprising the telescope. They were supplied by Cinema Television London, had a copper foil cathode 6" x 1", and a working potential of about 1300 volts. The three counters in each bank were connected in parallel to form a sensitive area about 6" x 3" (taking the sensitive area to coincide with the physical dimensions of the cathode, and the distance between the two banks in each telescope was $12\frac{1}{2}$ ". The counters thus defined a cone which enclosed a solid angle extending 13.5° either side of the zenith angle setting and 25.6° either side of the azimuth setting. The counters were mounted in the telescope frame so that the axis of the cone they defined would be parallel with the machined edges of the side plates. Thus in obtaining the zenith and azimuth angle settings it was necessary to set the edges of the telescope frames in the required directions.

SETTING UP THE TURNTABLE.

In setting the axis of rotation of the turntable vertical the following procedure was adopted:

A stand was set up on the top of the turntable and from it was hung a plumb-line consisting of a length of 40 gauge copper wire suspending a weight. The motion of the plumbline was damped by placing the weight in a beaker of water. Next a telemicroscope was set up on the turntable and focussed on the wire. The turntable was then slowly rotated and the plumb-line watched through the telemicroscope. When the tripod on which the turntable rotated was adjusted by levelling screws until the axis of rotation of the turntable was vertical, the plumb wire would not move in the field of the microscope. It was found possible to adjust the turntable until the movement of the wire in the field of the microscope was less than the diameter of the wire.

If the axis of rotation of the turntable were not vertical but inclined at an angle θ it can easily be seen that the plumb wire would describe a cone of semi-angle θ in a coordinate system fixed to the turntable when it was rotated. Thus taking the maximum movement of the wire as equal to its diameter (.004") and the field of the microscope to be

some 30" below its point of suspension, it can be seen that the error in the setting of the axis would be less than

$$\begin{aligned}(0.002/30)(180/\pi) &= 0.0038^\circ \\ &= 14''\end{aligned}$$

or about $\frac{1}{4}$ minute of arc. The zenith setting of the telescope would thus be reproducible with this accuracy after each revolution.

Unfortunately it was not possible to approach this accuracy in the setting of the azimuth angle adjustments with the same ease, or at any rate no exhaustive attempt was made to do so, as the magnetic declination was not known to better than about half a degree accuracy. The measurement of the east-west effect would, however, be much more sensitive to an error in the zenith than in the azimuth setting.

As the counters had been mounted in relation to the machined surfaces of the telescope frames, it was necessary to set the turntable stops so that the centres of the studs about which the telescope frames could pivot would be on the magnetic north south line. A table was set up level outside the door of the small hut used to house the apparatus, and a plumbline hung close to the northern edge of the table. At local noon a pencil line was drawn

on a sheet of paper pinned to the table in the position of the shadow of the plumbline. This was taken as the true north-south line and the magnetic north south line was drawn by allowing for the magnetic declination of 10°E . A wire was stretched tight and level from the inside of the shed, through the door, and above the top of the table parallel to the magnetic north south line. The turntable stops were then set so that the axis of the pivots of the telescope supports was parallel with the wire in the stationary positions.

Taking into account the accuracy with which the magnetic declination was known, the somewhat crude methods used, and the fact that the sensitive area of the counters might not coincide exactly with the cathodes, it was reckoned that the accuracy of the azimuth settings of the telescopes would be about $\pm 1^{\circ}$.

POWER SUPPLIES.

The high tension power supply used for the geiger counters was of the type used previously, having a half wave rectifier, condenser smoothing, and voltage regulator tubes in cascade for stabilisation. The circuit is shown in Figure 3.

Electronically stabilised 250 volt supplies capable of giving up to 80 m.a. with very little voltage change were used for the plate voltages. These units were of a type which has been adopted for general use in this laboratory.

The bias supply used employed a conventional full wave rectifier section with a VR75 voltage regulator tube across the output (Fig. 4).

COINCIDENCE AMPLIFIERS

The coincidence circuit used in the single telescope had operated satisfactorily for a period of several months although the adjustment of the bias voltage was somewhat critical. Mr. W.R. Parsons, who was assisting with the work for a time undertook to investigate some of the types of coincidence circuits described in the literature with a more stable unit in view. After some trials it was found that the circuit shown in figure (5) was capable of operating over a broad range of adjustment. The first two valves serve to amplify and invert the geiger counter pulses which are then applied to two of the grids of the third. These grids are normally biased sufficiently negative for the valve to be nonconducting. The positive pulses on the grids can only make the valve conduct if two arrive

simultaneously, for as long as one of the grids remains negative electrons cannot penetrate from the cathode to the plate. It was found that this circuit would work satisfactorily if the bias voltages were adjusted to be greater than a critical voltage by anything up to some 40 volts. Two units were built up using this circuit and mounted on the telescope frames, one to each. These units were altered at a later stage but the alterations will be described in another section.

MULTIVIBRATORS AND MECHANICAL RECORDERS.

With the single telescope a mechanical recorder made from a watch mechanism as described by Neher (1939) was used with the idea of obtaining a short resolving time, but it proved to be difficult to make dependable. As the counting rate was found to be of the order of 2 per minute it was decided to change to a more rugged type of recorder, the gain in dependability greatly outweighing the small loss of counts due to longer resolving time. The type of recorder obtained was the four figure non-setting type used in the P.M.G.'s Department, and had a maximum counting rate of 10 per second. A multivibrator with the circuit shown in Figure 6 was used to drive this recorder. The operation of the multivibrator circuit used in this way is described by Strong (1942, p. 285). Two units with this circuit were accordingly built up for use with the two telescopes.

PROBLEMS ENCOUNTERED IN OPERATING THE CIRCUITS
AND THEIR SOLUTION.

The two sets of circuits belonging to the two geiger counter telescopes were built up on the lines indicated above, and brought to the stage where each operated satisfactorily alone. When operated at the same time from the same power supplies however it was found that each time a count was received in one of the telescopes it caused both multivibrators to trigger.

An attempt to eliminate this trouble by using completely separate power units was unsuccessful, and also the use of shielded leads wherever possible was tried without complete success.. After tracing the interference with the C.R.O. its cause was isolated to the multivibrators themselves. A multivibrator with a pure resistance load will give a square wave-form at the output, which means that the current starts almost instantaneously, is constant for a short time, then stops almost instantaneously. With an inductive load as was presented by a mechanical recorder it was found that the waveform became distorted, and at the cessation of the current the collapse of the magnetic field resulted in large transient e.m.f.'s in the circuit which gave rise to "hash." This was being picked up by the other circuit and was sufficient to trigger its multivibrator. It was only necessary to have a very small pickup in the inputs to the coincidence units to cause the multivibrator to trigger.

The only way left to eliminate this trouble after shielding etc. had been tried without success was to try and develop a form of trigger circuit which would not give rise to "hash." The development of this circuit was along the lines described below.

First of all, to get an idea of the power output required, it was determined what size condenser charged to what voltage would work the mechanical recorder when discharge through it. It was found that a 16 μ F condenser charged to about 150 volts would supply enough energy when discharged through the recorder to actuate it in a positive manner. This gave a lead to the basis of the circuit, as shown in Figure 7.

The switch could be a power tube capable of carrying the current and normally biased part cutoff, being made conducting by a positive potential applied to the grid. (Fig. 7) As the pulse coming from the coincidence amplifier is negative it was necessary to invert it by using a driver valve. At the same time it would be necessary to lengthen this pulse by some means to allow the condenser time to discharge. On the basis of the above reasoning and finding the correct component values by trial and error the circuit shown on the right of the dotted line in Figure 8 was developed. The 6J7G is normally conducting and the 6L6 normally cut off by a large bias. When a negative pulse is impressed on the grid of the 6J7G it is made

less conducting causing a positive pulse to be passed on to the grid of the 6L6. This makes the 6L6 conduct and the 16 μ F condenser starts to discharge through the recorder. This causes a voltage drop across the recorder and the cathodes of the two valves swing positive, making the grid of the 6J7G still more negative with respect of its cathode. This ensures that it does not become conducting until the 16 μ F condenser has discharged sufficiently to allow the voltage across the recorder to drop and carry the cathodes back towards earth potential. The circuit then returns to its stable condition. If the negative bias is too small current flows through the 6L6 all the time and is only limited by the 1K resistor in its plate circuit and the impedance of the valve and recorder. As the bias is increased the circuit passes through a stage where it oscillates, then to the sensitive stage where it is operated. It was found that this circuit would operate from the coincidence amplifier provided the condensers in the output of the coincidence circuit and the input of this circuit were equal and fairly small. The output had a very smooth waveform which was improved by connecting an 8 μ F condenser in parallel with the recorder. There was no noticeable feedback through the input, and only a very small ripple transmitted back into the power supply leads. The circuit was therefore adopted in place of the multivibrators, and the interference caused by them eliminated.

A second source of trouble was discovered after the interference from the multivibrators had been eliminated. Owing to the use of radium around the laboratory, and the intermittent use of x-ray gear, it was found that over certain periods a large number of accidental counts were recorded. Independent pulses coming from both trays of a geiger counter telescope within the resolving time of the coincidence circuit were found to occur frequently with the high background radiation caused by the x-rays and radium. These could give rise to very misleading results in the experiments. As the source of this trouble could not be eliminated it was necessary to work on the coincidence circuits and try and shorten the resolving time to a point where the accidental counts would be reduced to a negligible number. The resolving time of the circuits being used was measured by the usual method of finding the counting rate of each tray of counters and also the number of accidental coincidences, obtaining the resolving time T from the standard formula.

$$A = 2N_1N_2T, \text{ where } A \text{ is the accidental rate}$$

N_1, N_2 the rates of the two trays,
and T the resolving time.

The value of T was found to be of the order of $50\mu\text{sec.}$

The Rossi type circuit (shown in Figure 8) was tried and found to have a resolving time of $8\mu\text{sec.}$ or less.

The 9001 valves were installed in the boxes containing the geiger counters to make the leads as short as possible. With this circuit it was found that the number of accidental counts was very greatly reduced and apart from noting the periods at which the x-ray plant was used and discounting them in computing the results, this was considered sufficient in dealing with the trouble caused by radioactive materials.

Electrical pickup set up by external sources such as relay make and breaks, sparks from the commutator of the turntable motor, etc. still caused many spurious counts which even the most careful shielding failed to eliminate completely. After a considerable amount of trial and error it was found that if the pickup was in the grid circuits of the 9001 tubes in the coincidence circuit, it could be amplified sufficiently to trigger the recorder amplifiers. Most of the pickup was traced to the lead coming from the high tension power supply to the geiger tubes. To eliminate this a filter consisting of a .1 μ F condenser and a 5 meg. resistor was installed in the H.T. lead to one tray of each telescope. As there still appeared to be some pickup at the grids of the 9001's it was decided to decrease the sensitivity of the coincidence circuit so that its input threshold would be above the pickup level but still below the level of the counter pulses.

To do this the screen voltage of the 9001's was increased slightly to make their cutoff less critical.

At this stage the circuits were found to work satisfactorily. The only adjustments were the bias of each discriminator valve in the coincidence amplifiers, and the bias on the 6L6 output valves of the recorder amplifiers. These were not critical in adjustment and once set did not have to be readjusted over long periods.

TIMING AND CONTROL MECHANISM.

Figure 9 shows the timing unit and the circuit by which it controls the apparatus, making its operation completely automatic.

The cycle of operations which this unit was designed to control includes the photographing of the recording instruments at the beginning and end of each hour's run, and rotating the gear from one setting to the other, so as to interchange the positions of the two telescopes in between runs. It was designed to time the runs to be exactly one hour long and to allow a minute in between for turning the apparatus round.

The basis of the timing unit is a synchronous gramophone motor of the segmented armature non-self-starting type. The speed of this type of motor is exactly governed by the frequency of the 50 cycle mains supply, which is regulated by the Hydro-Electric Commission so that an electric clock will seldom vary from the correct time by more than 10 seconds.

The armature of the synchronous motor having 77 segments, it rotates at $\frac{60 \times 100}{77}$ r.p.m. It was geared down by a 77: 100 spur gear reduction and a 60:1 worm gear to drive a shaft at exactly 1 r.p.m.

By means of a V-toothed dog clutch this shaft could be made to drive either a shaft at 1 revolution per hour through a 60:1 reduction or a sleeve carrying cams to operate a set of contacts controlling the rotation of the turntable. The 1 r.p.m. shaft geared to the motor and the shaft driven at one rev. per hour were both fitted to cams to operate contacts which we will call the minute and hour contacts respectively. Starting from a stage where the drive is onto the hour shaft the sequence is as follows:- After a time the hour contact and the minute contact close together. A photograph is taken and the dog clutch is thrown across, putting the drive onto the cam sleeve, which leaves the hour shaft stationary, and the hour contact closed. The cams on the sleeve cause the turntable to be rotated and when the minute contact closes again another photograph is taken and the dog clutch is thrown back, leaving the cam sleeve stationary and resuming the drive to the hour shaft. By the time the minute contact closes again the hour contact is open, and the two do not close together again until an hour later, when the events are repeated.

CLUTCH MECHANISM.

The clutch mechanism is shown in figure 10. The web of the clutch slides on a keyed portion of the shaft driven at 1 r.p.m. by the motor. It is moved by a forked yoke pivoted at middle, the other end of which is slotted. A pin on the disc shown engages the slot so that as the disc is rotated the clutch web is moved from side to side. Two pins project on the lower side of the disc and are engaged in turn by a claw on the piston of a compressed air cylinder. When air is let into the cylinder by a solenoid operated needle valve the disc is pulled round through half a revolution and the clutch is thrown from one position to the other. On the current through the solenoid ceasing, the air escapes from the cylinder and the claw returns to grip the other pin, so that next time the needle valve is operated the clutch is returned.

The details of the operation of the timer can be followed out on the diagram, figure 9. When the hour and minute contacts close together, current flows through the relay R2, shown in the top right hand corner, and charges up the 16 μ F condenser connected across the VR150. The charging current of the condenser is sufficient to operate the relay R2 which switches on lights

to illuminate the instrument panel and also switches the 12 volt current to the clutch solenoid. When the condenser charges up to the striking voltage of the VR150, the current flows through the tube and the relay R1. This relay switches the 12 volt current from the clutch solenoid to a solenoid on the camera which then photographs the recorders. When the minute contact breaks the current through both relays ceases. The 150K resistor serves as a leak for the 16 μ F condenser, and the .1UF condensers across the relays and the camera solenoid help to reduce "hash." The test switch is simply to short circuit the hour contact so that the timer can function every minute for testing purposes, and the photo switch enables extra photographs to be taken without operating the clutch. An indicator lamp on the instrument panel comes on with the lights when the turntable is in one setting, and not when it is in the other.

The cams which are driven round during the one minute interval between runs control the current to the holding magnet, which has to be switched off when the turntable is rotated, and a switch which, in conjunction with switchgear on the turntable sets the turntable motor going in the right direction. The magnet contacts simply break the circuit to the magnet so that the turntable can move away from its stationary position. The other contact works

an air piston similar to the one on the clutch. This operates a single pole double throw switch of the "ceiling-pull" type, i.e. one which goes one way on one pull and back on the next. This connects the current to the turntable motor through either of two leads on the 3-pin socket shown. The switch on the turntable, which is shown in Figure 11, consists of a reversing switch and a single pole double throw switch combined into the one mechanism. This switch is operated by the turntable as it reaches its stationary positions. If the reversing switch alone were used, this would reverse the motor at the end of the rotation, and the turntable would continue to rotate back and forth between its two settings. The s.p.d.t. switch combined with the reversing switch ensures that the motor will turn in one direction only when the power comes through one lead, and in the opposite direction when it comes through the other. Thus at the end of a rotation the turntable sets the switch for its rotation in the opposite direction, but at the same time switches the motor over to the idle lead, and the motor cannot start in the opposite direction until the "ceiling pull" switch is operated by the contact on the motor cam, switching the power over to this lead.

RECORDING CAMERA.

The camera which had been used to photograph the recorder with the earlier apparatus was not available for use with the double telescope, so it was necessary to effect a replacement. The only camera available at the time was a G.45 16mm. camera gun of the type used by the Air Force to photograph the effects of gunfire. This had to be converted to single shot operation for use as a recording camera.

In the G.45, which is magazine loading, the power is obtained from a small electric motor situated in the rear end of the camera. This drives the mechanism through a train of gears mounted along the inside of the case. No easy way could be seen to alter the camera by an internal modification, so it was decided to fit an external drive mechanism. It was found that one of the idler gears in the gear train turned exactly half a revolution per exposure and it was decided to introduce the drive onto this gear. It was accordingly mounted on a shaft extending through a boss fitted to the camera case. A rack and pinion movement was coupled to this shaft through a ratchet clutch, the rack being fitted to a compressed air cylinder of the type used on the timer clutch and the motor switch. On the forward movement of the piston, the camera mechanism would be driven far enough

for one photograph to be taken, and on the return stroke the pinion would slip back over the ratchet clutch. In order to ensure that the mechanism would always stop with the shutter closed, the ratchet clutch was made with only two teeth, so that it would always engage in one of two diametrically opposite positions.

The electric motor, and other parts of the camera such as heater elements etc., were removed, leaving only that part of the mechanism required for its operation.

Difficulty was experienced in making the converted camera completely light-tight, but by fitting baffles inside it a fairly satisfactory result was obtained. It was however necessary to prevent too much strong light from falling on it when in use. The operation of the camera was not entirely satisfactory, as it showed a tendency to miss occasional pictures through the film sticking. However, there were long periods during which this trouble was not experienced and during these the recording of results would be quite satisfactory.

OPERATION OF THE DOUBLE TELESCOPE APPARATUS

The apparatus was set up in a masonite shed, built away from surrounding obstacles so that there would be no interference to the cosmic ray beam detected by it except by the walls and roof of the shed itself, which were light and uniform. The turntable was

mounted on a concrete block in the centre, and the subsidiary apparatus was mounted on benches along one side, the connections from the telescopes to the power supplies and recording circuits being taken through flexible shielded cables.

The 12 volt supply for the timer was obtained from accumulators housed in a weatherproof box outside the shed, with a trickle charger permanently connected to them. The hut was wired for 240 volts A.C., and compressed air laid on from the laboratory supply.

PART II.

After the double telescope apparatus described in part I had been running for several months, the construction of a similar apparatus for use on Macquarie Island was begun. This project was financed by a grant from the Australian National Antarctic Research Expedition, and it was planned to send the gear to Macquarie Island in April, 1950, in the charge of Mr. K.B. Fenton. The object of this work was to obtain measurements of the east-west asymmetry at the latitude of Macquarie Island, some ten degrees closer to the magnetic pole than Hobart. The design of this apparatus was shared by Dr. A.G. Fenton, Mr. K.B. Fenton, and the author. It was decided at the outset to give each of these the responsibility for different sections of the gear as far as detailed design was concerned, Dr. Fenton taking responsibility for the construction of the geiger counters required, his brother for the design and construction of power supplies and recording circuits, and the author for the design of the control mechanism to make the operation of the gear automatic. General questions of design were decided at discussions which were held regularly with Prof. A.L. McAulay, whose suggestions and advice were of great help, particularly in the early stages.

These discussions also enabled those concerned to keep in touch with developments in each other's work.

A general description of the apparatus will be available elsewhere, and only those parts for which the author was responsible will be described here. These were the design and construction of a 35 mm. recording camera and drive mechanism, the modification of a predictor turntable to make it suitable for mounting the apparatus on, the design of relay systems by which the rotation of the turntable and the operation of the recording camera could be controlled by a clock, and the construction of a recording unit to support the camera, the instrument panel and suitable lights for photographing the instruments. Figures 12a and 12b show two views of the completed apparatus. Most of the parts designed by the author are confined to the space on top of the turntable and below the top of the bridge-like casting which supports the two geiger counter telescopes.

MODIFICATION OF PREDICTOR TURNTABLE.

The turntable was originally the base of a predictor unit and consisted of a sturdy aluminium platform mounted on large diameter ball bearings. The original predictor included a slipring contact system by means of which electrical leads could be brought to the top of the turntable and this was

retained to carry the power from the batteries to the apparatus.

All the predictor mechanism except for a shaft by which the turntable could be rotated was stripped from the turntable to make room for the telescope supports, the recording unit, the control system, and the rotating mechanism.

The rotating mechanism is shown in figures 13a and 13b. A reversible 24v, 1/10 H.P. motor drives a vertical shaft through reduction gears. This shaft carries on its lower end a pinion, contained in the housing beneath the turntable (figure 13a). This pinion can be locked to the shaft by means of knurled knob (not shown), and engages with the periphery of a large gear fixed to the solid base which carries the turntable. A friction clutch was included in the gear train to eliminate any shocks in starting or stopping the rotation of the turntable.

During the "runs" for the collection of data, the turntable has to be stationary in one of two positions 180° apart, and has to rotate from one of these positions to the other in between the runs. A space of 1 minute is allowed for the rotation, and the gearing was chosen so that the rotation would be completed in 40-50 seconds, making the movement of the heavy turntable as slow as possible while giving a 10-20 second margin.

In order to stop the turntable at the appropriate places, two sets of switches were used, each of which would cause the turntable to "home" to one of the two positions. By switching the power through one or other of the two sets the turntable could be made to move to the corresponding setting. These switches operated as follows: A drive was taken off from the rotating mechanism to a gear driving a cam plate which can be seen on the right hand side of figure 13b. The gear ratio was chosen so that this cam plate would rotate at approximately the speed of the turntable and as its drive was taken from the gear train on the turntable side of the slip clutch its position relative to the position of the turntable would not be altered by the clutch slipping. A raised cam was fitted to the periphery of this plate so as to engage handle-like pins on the shafts carrying the mercury switches at certain points in the rotation of the turntable.

If, for example, the right-hand set of switches is in circuit, the turntable will rotate until the cam lifts the pin which tilts this set. As the pin rides up the cam the motor is switched off, and if the turntable has sufficient momentum to carry it past the "off" position, the pin will ride further up the cam, and the motor will be started again in the reverse direction. Thus the turntable will be

brought back to rest at a point where the pin is about halfway up the cam face. this method of positioning the turntable gave an accuracy of setting of $\pm 1^{\circ}$. When it is required to rotate the turntable from one position to the other, the current is switched from one set of switches to the other and the turntable then rotates until these switches are brought to their dead-centre position by the action of the cam.

CONTROL GEAR.

A system of relays was designed to control the operations of recording information and changing the setting of the apparatus. Two contacts were fitted to a clock and arranged to close at the hour and one minute later. The first contact was made to operate the recording camera, and initiate the rotation of the turntable, the second contact to operate the recording camera only.

The Clock: The clock used was built round the mechanism of an eight day clock supplied by the firm of Tayclox. The contacts consisted of silver wire let into a lucite disc mounted concentric with the hour hand shaft on the back of the clock frame. The hour hand shaft was fitted with a wiper contact to pass over the silver contacts on the disc, which were spaced 6° apart.

The original clock face was replaced by a smaller one made photographically to have white figures on black. The reduction of the clock face made possible a smaller instrument panel, bringing the figures on the different instruments into better proportion with each other.

"Two Second" Relays: In order to make the contacts on the clock rugged and reliable, it was necessary to make them of such a size that it would take the wiper contact about 20 seconds to pass over the face of each. In order to reduce wear and tear on the rest of the control gear, in particular the camera drive, a special relay was interposed between the clock contact and the rest of the relays to keep the current on them for a period only long enough for the operation of the camera drive, about 2 sec.

This relay was made using a modified overrun control. (Figure 14). On the closing of the first clock contact, C1, the current charging a 40 μ F condenser closes the relay R3 for a fraction of a second. This allows a pulse of current to pass through the solenoid S, which pulls back a spring loaded arm by means of a rack and pinion movement. This arm, in its rest position, keeps a micro-switch (MS) open, so that when the solenoid pulls the arm away the microswitch closes.

When the current through the solenoid ceases, a pawl on the arm engages a ratchet wheel which is rotated as the arm moves back under the tension of its spring. The ratchet wheel is loaded by a mechanical escapement and this limits the speed at which the arm travels back. An adjustable trip releases the pawl after the arm has travelled a certain distance, and it then flies back freely to its rest position and opens the microswitch. According to the position of the release trip, the arm moves for a longer or shorter period under the escapement, hence the time for which the microswitch is closed can be adjusted by moving the trip. This period can be adjusted from 0.5 sec. to 3 sec.; the period used being about 2 sec. The microswitch closes the circuit of either R_2 or R_3 , according to which clock contact is closed. A 10K resistor was connected across each 40 μ F condenser as a leak.

Mercury switch relays: The relays R_1 and R_2 consist of 24 volt solenoids which tip mercury switches. The relay R_1 carries 3 mercury switches. One of these operates the relays which initiate the rotation. The other two, which are in parallel are also in parallel with the two on R_2 and close the circuit to the camera drive and the lights on the recording unit. The relay R_1 closes first, operating the camera and the rotating switch, and the relay R_2 operates a minute later.

The turntable motor is series wound with one end of the field earthed. To reverse this motor it is necessary to reverse the connections to the armature from the +24V lead and the free end of the field. As described earlier each of the two sets of switches operated from the turntable drive constitutes a reversing switch with an off centre position, and the current to the armature is passed through one or other of these sets. The relays which initiate the rotation are therefore required to switch the leads from the 24V supply and the free end of the field to one or other reversing switch. This is done by having two three-electrode mercury switches mounted to form a double pole double throw switch operated by two solenoids R_4 and R_5 . The mounting for these switches is top heavy, so that they will sit stably in either position. Leads are taken from one side of the two solenoids R_4 and R_5 to the third mercury switch on R_2 . The leads from the other sides of the solenoids are taken to two contacts which earth onto the raised portion of the cam which operates the positioning switches. When the turntable is in one setting, the solenoid which will change the d.p.d.t. relay to its opposite position is earthed, so that the next time the relay R_1 is energised the d.p.d.t. relay will be pulled across and the other set of positioning switches brought into play

to make the turntable home to its other setting. The connections to these switches can be followed out in figure 14.

Turntable setting indicators: It is necessary to have an indicator on the instrument panel to show the position of the turntable at the time of a photograph. Two indicators are mounted above the two recorders on the panel. These consist of the letter W mounted over a hole in the panel. The W shows up only when illuminated from behind the panel. Two 6v globes are mounted behind the letters and one or other of these is switched on at the time of a photograph to show which recorder corresponds to the west pointing telescope. The power for these globes is taken from across one of the 6v globes which illuminate the instrument panel when it is photographed. A common lead to the globes was taken from the recording unit, and the other leads go to contacts which earth to the raised part of the cam disc (Fig. 14).

RECORDING UNIT.

The recording unit consists of a framework to support the camera, the panel carrying the instruments to be photographed by the camera, and lights to illuminate the instruments. It was made up from tubing and sheet metal in the form of a conical rectangular tunnel carrying the camera & the

apex and the instrument panel at the base. The lights were let into recesses in the sides and the whole of the inside of the tunnel painted white. In addition, a cover was made to fit over the back of the instruments in the form of a tin box with the inside painted black. It can be seen that by painting the internal surface of the tunnel white, most efficient use was made of the light by diffusing it over the instrument panel, and by ensuring that all the field except the lettering on the instruments should appear black, an easily read film record was obtained. The instruments mounted on the panel were a clock, the mechanical counters for the two telescopes, a barometer, a dial thermometer, lights to indicate the setting of the turntable, and a notice board for other data.

THE RECORDING CAMERA.

No reliable camera of a suitable type was available for use on the Macquarie Island gear. The converted G.45 camera gun used on the double telescope apparatus had not proved to be completely reliable and in view of the importance of using the time available on the island to the best advantage, it was thought undesirable to risk the loss of results through faulty operation of the recording camera. It was decided to try and design a reliable camera of a type which could be used on the

island gear and as a replacement on the Hobart gear, bearing in mind that if a suitable design of camera could be constructed it would certainly find other uses in the laboratory. •

The design of the recording camera was regarded as something more than simply the design of part of a complex piece of apparatus. At the outset a review of the features desirable in such a camera was made, and then the construction of a prototype incorporating as many of these features as possible was undertaken. Apart from its use for recording the readings on instruments at regular intervals other uses such as recording plant growth, photographing a Wilson cloud chamber, automatic microphotography etc., were envisaged.

Several features of the camera were decided by external factors. First, the film size, 35 millimetre, was chosen because this size of film was more readily obtainable in bulk than 16 mm. film. The film capacity was based on the amount of film required for the cosmic ray apparatus per week. After the use of standard half size frame size ($\frac{3}{4}$ " x 1") giving 16 frames per foot had been decided on, the estimated film capacity required was 25 feet. The lens chosen for use was the 5 cm. f3.5 Centaur made by Waterworth, Hobart. For the sake of standardisation it was decided to make the thread on the lens mounting ring, and the distance from the front of the mounting ring

to the film plane, the same as in the Leica 35mm. camera, in order that it could be used with lenses and fittings commercially available. It was fairly obvious that the features of the camera mentioned above would not make its design any more difficult and so were adhered to from the outset. Other features, however, had to be considered according to whether or not they were practicable.

For the automatic operation of the camera, it was necessary to have the film transport and shutter both operated from the same mechanism. The idea of driving both these by turning a shaft projecting from the camera was adopted, and the design aimed at having the complete cycle of operations necessary for making an exposure and moving the film on completed in one revolution of this shaft.

In cameras previously used for recording it had been found necessary to run focussing strips each time they were set up to ascertain the best focus, exposure etc., to use. To eliminate this tedious procedure in the event of the camera being used for a variety of jobs it seemed desirable to make provision for focussing by having a removable back, especially as the camera would be used mostly over short distances where focussing is critical.

It was thought possible at the same time to provide for the fitting of a lamp and condenser system to the back of the camera. For use in accurate cloud chamber work, where it is desirable to re-project the images of tracks through the same lens system with which they are photographed, this feature would be necessary.

Another feature which would make the camera more versatile would be its easy modification for continuous film transport for use in recording the traces of an oscilloscope.

Construction of the Camera: Figure 15 shows the internal layout of the camera as it was finally built. The film "f" passes from the spool "h" along the back of the shutter box, over the feed sprocket "g", and onto the takeup spool "l". A flat circular pressure pad "k" in a screwed plug "p" holds the film flat on the gate. The shutter was copied from the roller blind focal plane type used in the Leica, and the threaded lens mount "m" was made long enough to enable the camera to be focussed from infinity down to about 9 inches by screwing the lens out, a locking ring being provided for clamping it once in the right place.

It was found that the shutter presented most difficulty in the construction of the camera. The possibility of obtaining a suitable shutter commercially was considered first, and of those available the Compur type of shutter seemed to offer the greatest chance of success. Owing to the type of lens mount which had been decided on to make the range of focus as large as possible, it would have been necessary to mount such a shutter on the front of the lens. This would probably have proved satisfactory, but shutters of this type were not readily obtainable and the chance of constructing them successfully was considered slight owing to the large amount of fine work involved. Some simpler types, such as those used in cheap box cameras were considered, but it was thought worthwhile to try and make a shutter with variable exposure time. The alternative was the focal plane type of shutter. After studying the principles of all the types of focal plane shutter on which information was available, such as the guillotine, louvre, metal blind and cloth blind types, it was decided to make an experimental copy of the roller blind shutter as used in the Leica. This was done, and although it was only roughly built to see what difficulties would present themselves in its construction, it was found to give very promising

indications, and moreover to be easier to construct than at first it appeared. Reliable operation at different exposure times was obtained even with this model.

The principle of the shutter used in the Leica can best be followed out by inspecting one of these cameras, and only an outline will be given here. The blinds which form the shutter are wound on rollers on either side of the gate, as shown in Figures 15 and 16. The operation of the shutter may be divided into two parts, the setting and the release. To set the shutter both blinds are wound across the gate together, letting no light through. To make the exposure the blind b (Fig. 16) is released first and the blind d a short time later. The blind b when released is wound onto the spring loaded roller, uncovering the gate, and exposing the film. The following blind d closes the gate. The exposure adjusting mechanism consists of a catch which holds d stationary when b is released, and an adjustable trip which releases d after b has travelled a certain distance. The setting of the shutter is carried out by turning the shaft on which the large roller assembly is mounted, and the exposure is made when this shaft is released.

It was decided that the camera could be made more versatile if the shaft for operating the shutter were taken out through the main camera casing separate

from the film sprocket shaft. This would mean fitting a small external gearbox to enable the shutter and transport mechanism to be driven from one other shaft, but any modification such as adapting the camera for continuous film drive could be made by altering the gearbox only.

A prototype camera was constructed, and two views of its parts are shown in Figures 17a and 17b. All the moving parts are mounted on one sideplate. The gearbox can also be seen in the enlargement, Figure 18. The drive is applied to the shaft "a" on which a crank is shown in the photograph. The shutter is operated in the following way. The gear "b" which runs on a stub axle fixed to the outer plate carries a short pin which engages with a similar pin on a disc fixed to the shutter shaft. The gear is spring loaded so that the two pins are normally engaged. The gear "b" meshes with a gear on the driving shaft, which also carries a sloping flange "c". This flange lifts the gear "b" by the small disc "d" at a certain point in the rotation of the drive shaft and so disengages the pin on b from that on the shutter shaft, releasing the shutter to make the exposure. On turning the drive shaft a little further, the gear "b" is allowed to drop back ready to wind up the shutter again.

The film transport sprocket is driven intermittently so that the film may be stationary when the exposure is made. A gear "l" on the sprocket shaft is driven in steps of half a revolution by a gear "f" from which about half of the teeth have been cut away. The gear "f", which is mounted on the drive shaft has to enter into mesh with "e" every time it takes up the drive to the sprocket shaft, and to ensure that it would do this cleanly a locking sector was fitted to the driving shaft in the form of a semicircular disc mounted concentric with the gear "f" and opposite to the teeth. This engages with concave sections of a locking plate "g" attached to the gear on the sprocket shaft. This locking device, as well as ensuring that the gears will mesh cleanly each time, keeps the film stationary during the exposure.

The takeup spool shaft is driven from the gear "e" through a train of gears on two idler shafts. On one of these shafts is a friction clutch so that the takeup spool is able to slip. This is necessary because of the different diameter of the film on the spool at different times, and if the spool could not slip it would tend to take up the film quicker than it passed over the sprocket, either tearing it or pulling it over the teeth of the sprocket. The gear ratios and the spool diameter were made such that the rate of takeup of the film to the spool when empty would be just a little

faster than the rate at which it would feed over the sprocket. Thus the film is always kept tightly over the sprocket, as it is always necessary for the friction clutch to slip a little.

The case of the prototype camera was fabricated from sheet metal and of straightforward construction. Flat black paint was used over as much as possible of the inside of the case, and black velvet used to make the lid light-tight. For mounting the camera a block was screwed onto the sideplate and tapped for 1/4" Whitworth. Two grooves were cut at right angles across this block so that a "three ball two groove" type of mount could be used.

Good pictures were obtained with this camera. Enlargements of several outdoor shots showed that the exposure over the whole frame was quite even, showing that the shutter was operating satisfactorily, and good, even framing showed that the film was being moved on correctly. The prototype camera has, in fact, had several months use both in Hobart and on Macquarie Island, and has operated very satisfactorily.

Camera Drives:- As has been described, the camera was designed so that the operations involved in making an exposure and moving the film on would be completed in one revolution of the drive shaft. It was necessary to supply the motive power from an external mechanism.

The most useful type of drive appeared to be one which could be operated from an accumulator of 6 or 12 volts, and constructed so that on closing the circuit it would turn the camera shaft through just one revolution. With this, the camera could be operated by closing a contact in some external circuit when it was required to take a photograph.

The main problem in constructing the drive was to limit the transmission of power to one revolution of the drive shaft. A stop of some form, operated by a solenoid was needed to do this. The idea for the first type of stop constructed was based on a release previously used to allow a spring loaded shaft to turn through one revolution.

This release consisted of two offset stops operating on a peg projecting from the periphery of a disc on the shaft. One stop normally prevented the disc from turning. When it was pulled aside by a solenoid the other stop was brought in behind the normal position of the peg, so that before the shaft had quite completed a revolution, the peg would come up against it. On the release of the solenoid, as one stop moved out of position the other moved in, so that the peg would merely drop from one onto the other. This type of release had been found to be very positive in action and it was decided to use something similar to limit the camera drive to one revolution. A problem presented itself at this stage, however.

If such a stop was used to limit the rotation of a shaft driven through reduction gears by a small electric motor, a good deal of strain would be thrown on the mechanism when it pulled the shaft up at the end of the rotation, as this would stop the motor dead. One way of overcoming this was to put a friction clutch in the drive mechanism so that it could slip when any undue strain was put on the mechanism. It was realised that this clutch would have to be at least tight enough to transmit the drive directly, and the release catch would still be handling a larger torque than previous experience had shown to be desirable if positive action was to be obtained without using a solenoid which would draw a much larger current than the motor.

A much better idea was to employ a clutch which could be made to engage for one revolution only. Such a one was constructed and its operation can best be explained by referring to Figure 19. The gear "a" is driven by a small electric motor through gears not shown in the diagram, and is coupled to the drum "b". The gear and the drum are both free on the shaft. Round the drum is wound either a wire or a metal band, one end fixed to a peg on the disc "c" and the other to a peg on a larger disc "d". The disc "c" is attached to the shaft which is coupled to the camera through the coupling at "e", while "d" rides

loosely on the boss of "c". Either a light spring can be used to draw the two pegs together and keep the band firmly round the drum, or the band can be bent to a smaller diameter than the drum so that it tends to tighten on it. An escapement type of catch which is worked by a solenoid, operates on a peg on the disc "d", as is shown at "f". The direction of rotation is such that the end of the band attached to "d" is the leading one. While the motor is running the drum "b" rotates continuously. If the disc "d" is released, the band tends to tighten on the drum, any friction between the leading end and the drum being multiplied around the drum and "c" is pulled round. This is the everyday principle employed, for example, when a large tension in a rope is controlled by winding it several times round a post and using only a small force on the end. When "d" comes up against the stop, the band tends to pile up on itself and loosens off the drum.

The drive built up using this clutch mechanism was found to work most effectively. The transmission of a torque which was ample to operate the camera was controlled positively, very little strain being put on the release. An advantage of this type of drive is that after the rotation of the camera shaft is completed, the motor can be left running under practically no load.

Construction of Copies of the Camera: The prototype camera was put in the hands of the Physics Department Workshop, which was asked to make a number of them as it could be seen from the performance of the prototype that they would be useful for a number of purposes. Mr. E. Campbell, who was in charge of the construction of the cameras, went over all the details of the prototype and, while conforming to the principles of its operation, affected alterations which would make the cameras easier to construct in numbers and a much more solid instrument. Most of the alterations were made to avoid the fabrication of parts, for example, the bodies of the cameras were cast in aluminium instead of being built up from sheet, and so on.

Drives: It was decided to try out some different ideas for the camera drive before starting the construction of a number of these units for the cameras being constructed by the Department Workshop, and a unit different from that built for use with the prototype camera is shown in Figure 20. In this unit a friction clutch was used to avoid placing too much strain on the motor and release. As can be seen in the photograph, a worm reduction was used. Two of these units were made, and in both of them the same kind of release catch as in the previous drive was used, but in one the friction clutch was placed on the worm spindle and in the other on the gear shaft.

Spring loaded cone clutches were used in both cases. These drives both proved satisfactory, but comparison showed that the self tightening clutch principle of the first was superior to the friction clutch idea used in the second two.

Another drive unit was built up using a 12 volt windscreen wiper motor and a self tightening clutch. This clutch is shown diagrammatically in Figure 21. A drum "a" is driven by the motor through the shaft "b". Fixed to the shaft "c" which couples to the camera drive shaft is a disc "d", which carries two shoes "e,e". These are pivoted on the pins "f,f" projecting from the disc "d", and two light springs "g,g" are fitted between them so as to press them outwards against the inside of the drum "a." Leather pads "h,h" form the contact surface between the shoes and the drum. When the drum rotates in the direction of the arrow, the friction between the leather pads and the drum help the springs to expand the shoes, and in this way the clutch gets its self tightening action. The clutch is easily controlled, however. Pins "k,k" in the free ends of the shoes project through slots "l,l" in a disc "m" which is loose on the shaft c. When this disc is held stationary, the pressure exerted on the pins "k,k" loosens the shoes and disengages the clutch. A short stop "n" projects from the disc "m", and the

plunger "o" of the solenoid "p" can be brought into its path when current is passed through the coil. The plunger of the solenoid is made in two sections, the one towards the clutch being brass, the other of steel. As the steel part is drawn towards the centre of the coil, the brass part is pushed out.

The solenoid and the motor are connected in parallel. When current is passed through them and the drum "a" rotates, the clutch engages, turning the shaft "c", until the stop comes up against the solenoid plunger. When the current is switched off, the plunger is withdrawn by a spring, and the momentum still possessed by the motor is sufficient to carry the stop on to a position under or just past the plunger. When the current is switched on the next time, the plunger comes down behind the stop, and the clutch is free to make a full revolution before being disengaged again.

This drive was found to be completely reliable, and it was copied in making drives for the cameras built by the workshop. The drives were built into steel boxes about four inches square, and the cameras mounted on the side, a flexible coupling being used to transfer the drive to the camera.

Conclusion to Description of 35mm. Cameras
and Drives:-

The cameras constructed by the workshop have been tested and found satisfactory. Four of them, and also the prototype, have been used on cosmic ray gear on Macquarie Island. These were pushed through ahead of the rest in time to be sent to the island, and consequently their initial tests were curtailed. Several minor troubles were encountered, but these were all remedied within the first few weeks, after which the cameras settled down to reliable operation. One other has been installed on the cosmic ray gear at Hobart, and another has been used in connection with other research, with very satisfactory results. Several others have been completed and tested.

As the project of designing and constructing these recording cameras and drives involved others beside the author, it would be as well to point out the extent to which the author was involved. The basic ideas in the design of the prototype camera came out of discussions between the author and Mr. McMahon, of the Photographic Section, although the construction was the work of the author, with some technical assistance and advice from the staff of the workshop. The first drive was entirely the author's work, both in design and construction.

The second drive, with the exception of some of its components was also the author's work, as was some of the initial work on the third drive. The drives using the expanding shoe type of clutch were constructed entirely by the workshop, the design having been arrived at in discussions between Mr. Campbell and the author after the earlier types of drive mechanism constructed by the author had been thoroughly tested.

PART III.

MODIFICATION OF DOUBLE TELESCOPE APPARATUS.

It was planned to continue the measurements of the East-West asymmetry at Hobart during 1950-51 on a parallel schedule with that followed on Macquarie Island. To do this successfully it was necessary to carry out some modifications to the Hobart gear so that the results would be directly comparable. The main difference between the two sets of apparatus lay in the size of the counter telescopes, the Macquarie Island gear having been planned so that a statistically significant value of the asymmetry could be obtained in three weeks or a month. When the first double telescope apparatus was built at Hobart its size was limited by the number of counters available, but the difficulty of constructing reliable geiger counters in sufficient numbers for larger counting areas was overcome during 1949. The Hobart apparatus was therefore extended to enable counter trays of about the same size as those used on the Macquarie Island setup to be employed. This made the counting rates of the two sets of apparatus about equal, so that the rate at which data could be accumulated would be the same for both stations.

As well as increasing the physical size of the telescopes, improved circuits, the same as those developed by Mr. K.B. Fenton for the Macquarie Island gear were installed. The circuit diagram of these is given in Figure 22. The pulses from each tray of counters are fed into a univibrator stage, which gives a uniform output pulse independent of the size of the input. The pulses from these are fed to a Rossi type coincidence circuit, which then feeds into a scale-of-two stage. The output from the scale-of-two is used to trigger a thyatron which operates the recorder. The power supplies previously used were retained. As the author was not directly connected with the design of these circuits they will not be described in further detail here.

The timing and recording section was not altered except that the contact operated by the minute shaft was replaced by a micro-switch, and a compression spring attachment (Fig. 9) was fitted to the clutch lever to make its operation more positive. No other modifications were needed to make this section of the apparatus thoroughly reliable.

The G45 camera used previously was replaced by one of the new 35mm. recording cameras, but this did not entail any alteration in the setup, the drive mechanism being simply connected in the place of the release solenoid of the previous camera.

The modifications of the apparatus had been completed by the time the other setup had been transported to Macquarie Island and assembled there, so it was possible to start the programme of work at the two stations very nearly at the same time.

PART IV.

RESULTS OF THE HOBART EXPERIMENTS.

The results which will be discussed here were obtained with the first double telescope apparatus (Part I) during the period from June 30, 1948, to June 23, 1949, and with the modified setup (Part III) between June 22, 1950, and February 16, 1951. These results are collected in Table I.

The description of the setting of the telescopes and the period for which the apparatus was run at each setting is given in the left hand column, the total number of counts recorded and the total recording time for the west and east positions of both telescopes being given in the next four columns. The letters D.T.I. in the last column indicate that the results were obtained with the first apparatus, and the letters D.T.M. show that the modified telescopes were used.

From the data given in Table I a value of the asymmetry for each zenith angle and lead thickness was calculated. These are given in Table VII. To obtain the values in Table VII, it was necessary to combine the results from the two telescopes, and also the results from different runs. This was done by calculating the asymmetry for each telescope in each run (which gave, for example,

six determinations of the asymmetry for 60° no lead and taking a weighted mean.

If J_W and J_E are the counting rates for the west and east positions of a telescope, the asymmetry is given by

$$a = 2(J_W - J_E) / (J_W + J_E)$$

The probable errors of the rates have been taken as

$$\delta J_W = 0.6745 J_W / N_W^{1/2}$$

and

$$\delta J_E = 0.6745 J_E / N_E^{1/2}$$

where N_W and N_E are the numbers of counts used to determine J_W and J_E .

The probable error of a has then been obtained by using the relation

$$\delta a = 2 \{ (\delta J_W)^2 + (\delta J_E)^2 \}^{1/2} / (J_W + J_E)$$

In the case of the results obtained with the modified apparatus it was necessary to apply a correction to the counting rates by subtracting 1 per minute or 60 per hour from the rates. The determination of this correction, which was for accidental coincidences, will be discussed later. The correction was taken to be the same at all angles.

In applying the correction, the asymmetries were all calculated as described above. Then, since the correction reduces the value of $\frac{1}{2}(J_W + J_E)$ by 60, where the rates are counts per hour, but does not alter the difference $J_W - J_E$, all the values of the asymmetry

determined with the modified apparatus were multiplied by

$$\frac{\frac{1}{2}(J_W + J_E)}{\frac{1}{2}(J_W + J_E) - 60}$$

No correction was applied to the results from the first apparatus, as will be explained later.

To combine the determinations of the asymmetry at each setting, the individual values were assigned weights inversely proportional to the square of their probable errors (Bond, 1935, p.81) and a weighted mean taken. The probable error of the weighted mean was obtained by combining the probable errors of the individual determinations according to the relation given by Bond (1935, p. 83), i.e.

$$\overline{\delta a} = \pm \frac{n}{1+n} \sqrt{\frac{1}{(\delta a_1)^2}}^{-\frac{1}{2}}$$

The discussion of the results given in Table VII will be deferred until after the discussion of the theory.

Correction for Accidental Coincidences: When two trays of counters are used in coincidence, a count can be recorded when two unrelated particles discharge the trays within the resolving time of the circuit, and such a count is indistinguishable from true coincidences due to single particles. Such counts are known as "accidentals." For a twofold coincidence setup, the accidental rate is given by

$$A = 2N_1N_2T$$

where N_1 and N_2 are the counting rates of the separate trays and T is the resolving time of the coincidence circuit.

Before discussing the accidental rates of the telescopes used, a relevant characteristic of the geiger counters used should be discussed.

In the earlier setup, the usual copper in glass type of counters were used. These had a background counting rate of approximately 1 per second, the cathode size being 6" x 1". During the construction of the Macquarie Island gear the external cathode type of counters were adopted because they were easier to construct and had improved plateau characteristics. Soda glass had to be used because of its lower resistivity, but unfortunately the glass used with slightly radioactive, probably due to traces of K^{40} , and this caused the counters to have a higher background rate than copper in glass counters of a similar size. An experiment on one of these counters showed that the cosmic-ray background rate was slightly more than 1 per second, and the total background rate was 4.6 per second. The background rate due to cosmic rays was nearly the same as the background for the copper-in-glass counters in proportion to their

size, so the latter do not appear to suffer from radioactivity in the glass to any noticeable extent.

The background rate of the counters affects the accidental rate of a coincidence setup. With a background rate about four times as great, the accidental rate would be increased some sixteen times for twofold coincidence setup. The Macquarie Island apparatus, and consequently the modified Hobart one, was designed with the characteristics of the copper-in-glass counters in mind, and it was estimated that the accidental rate would be negligible considering the accuracy required in the experiment. The high background of the external cathode counters was not discovered until it was too late to alter the apparatus, and consequently the results had to be corrected to allow for the higher accidental rate.

A separate experiment was conducted to obtain a correction. Two trays of counters were assembled similar to those on the telescopes and used with a spare coincidence circuit similar to those in use on the apparatus. The following counting rates were measure:

	N_1/sec	N_2/sec	A/sec
(a) Trays flat on level table, separation 2 metres	29.31	45.33	0.0155
(b) As for (a), radioactive sources present	57.51	77.86	0.0378

	N_1/sec	N_2/sec	A/sec
(c) As for (b) with stronger sources	91.26	123.55	0.0789
(d) As for (a), separation 1 metre			0.0172
(e) As for (a), separation $\frac{1}{2}$ Metre			0.0298
(f) As for (e), but with 10" lead on table between trays			0.0227

The measurements a, b, and c gave a method of obtaining the resolving time of the circuit, for if the rate A is made up of accidentals and showers, the shower rate would be independent of the added background of the trays in b and c, and we would have

$$A = 2N_1N_2T + S,$$

where S is the shower rate. The values of A were plotted against $2N_1N_2$. This gave a straight line whose slope gave the resolving time T as 3.2 microseconds. The intercept on the vertical axis gave the shower rate S, the value being 0.008 per second.

Comparison of e and f showed that a few direct rays were recorded in e, so that the rates for a, d, and f give an indication of how the accidental rate varies with the separation of the counters. It can be seen that the dependence here is not critical. In view of the difficulty of relating the accidental rate determined here with the accidental rate of the telescopes because of the different relative orientation of the trays in both cases, it was decided for the correction to take

the value 0.0167 per second, or 1 per minute, as a reasonably good estimate of the accidental rate of the telescopes in any of the settings used in the experiments.

Referring back to the first double telescope apparatus it can be seen that the excessive background rate was not present with the counters then used. The accidental rate was thus smaller than when the external cathode counters were used by a sufficient amount for it to be neglected in the calculation of the asymmetry.

PART V.

THEORY OF THE ASYMMETRY.

It is assumed that in latitudes above the knee of the latitude effect the primary radiation is isotropic above the atmosphere, as was argued in the Introduction. This theory, therefore, treats the asymmetry in the radiation which arises because the secondary mesons which form nearly all of the penetrating component at sea level undergo slight deflections in the earth's magnetic field.

If the magnetic field were absent, absorption effects in the atmosphere would result in a directional distribution of the intensity at sea level which would be symmetrical about the vertical, the intensity being a function of the zenith angle θ . The intensity at an angle θ would then be given by an equation of the form

$$j(\theta) = j(0)f(\theta) \dots \dots \dots (5.1)$$

where $j(\theta)$ is independent of azimuth. The function $f(\theta)$ has been found experimentally to be approximately equal to $\cos^\gamma \theta$ with $\gamma \approx 2.2$ for the total radiation. Since, as will be shown later, the change in direction of the path of a meson of even very low energy is not more than a few degrees, the effect of the deflections will be to slightly upset the symmetrical distribution which would be found in the absence of the magnetic field. The intensity of positive particles which would be found at a certain zenith angle in the east-west vertical plane in the symmetrical distribution will be found

a few degrees to the west, and for negative particles the displacement will be to the east. This leads to asymmetries in the negative and positive radiation which are of opposite sign, and since there are more positive than negative mesons there is an asymmetry in the total radiation.

The general lines of Johnson's theory have been followed here, i.e. the deflections suffered by mesons with different final energies and directions have been calculated first, and then the asymmetry which arises because of these deflections. The main difference between the treatment given here and that given by Johnson lies in the use of graphs and numerical integration as an aid to calculation. This has enabled empirically determined data to be used without the difficulty of finding analytical expressions which would lead to a more complicated treatment. The use of these methods also makes it possible to arrange the working so as to show clearly where various assumptions are used and their significance. The limitations of the methods as far as accuracy is concerned do not matter in view of the comparatively large probable errors of the results with which the theory is to be compared.

Now a meson with an energy ϵ_{moc}^2 has a range in air of M grams per square centimetre, and the relation between ϵ and M is given graphically by Montgomery (1949, p. 353). From pressure-altitude tables (Montgomery, 1949, p. 347) it is possible to calculate the amount of air in grams per square centimetre which a particle has to penetrate between any point on its path and the apparatus at sea level. If to this is added the residual range in air corresponding to the energy with which the particle arrives at the apparatus, we obtain the value of M for the particle at that point. From this can be obtained the energy, and from the energy the radius of curvature by equation (5.6). In this way it is possible to find the value of $1/\rho$ at any number of points along the path, and by numerical integration the value of

$$\delta = \int_0^{S_1} \frac{ds}{\rho} \dots \dots \dots (5.7)$$

which gives the total change in direction between the distance S_1 along the path and sea level. S_1 can be chosen to correspond with the height at which the mesons are produced.

To facilitate the calculation of δ for a number of final energies and directions of arrival, a table (Table II) giving the residual air mass in grams per square centimetre for equally spaced points along straight

paths inclined at 0, 15, 30, 45 and 60° to the vertical, and a graph of the curvature $1/\rho$ against residual range was drawn. The procedure was then as follows: for a particle which arrives at an angle of say 45° with a final energy corresponding to a residual range of for example 100 gms/cm.² of air, 100 was first added to each of the values in the 45° column of Table II. From the graph, (Figs. 23 and 24) the corresponding values of $1/\rho$ were read off, and the integral was then obtained using Simpson's Rule for numerical integration, i.e.

$$\int_a^{a+nh} f(x) dx = \frac{1}{3} h \left\{ f(a) + f(a+nh) + 2[f(a+h) + f(a+3h) + \dots] + 4[f(a+2h) + f(a+4h) + \dots] \right\} \dots 5.8$$

The results of the numerical integrations are given in Table III, which gives δ in radians as a function of zenith angle of arrival and final residual range in air. The corresponding final energies are given.

It is interesting to compare the values of δ obtained by this method with those obtained by Johnson (Table I in his paper). The values are greater than Johnson's, particularly at the higher energies.

Johnson used an approximation that the rate of energy loss is constant and independent of energy, although this would not cause an error of more than a few percent. He also used the relation

$$p = e^{-h/h_0} \quad \text{---} \quad 5.9$$

for the pressure in atmospheres at a height h instead of the slightly more correct values given in the tables. The difference appears greater than could be due to these two causes, and it is attributed to a difference in the expression used for the curvature. Where we have taken

$$\delta = \int_0^{s_1} \frac{ds}{\rho} \quad \text{---} \quad 5.10$$

for the deflection, Johnson has taken

$$\delta = \lim_{s_1 \rightarrow \infty} \int_0^{s_1} \left(\frac{1}{\rho} - \frac{1}{\rho_0} \right) ds \quad \text{---} \quad 5.11$$

where ρ_0 is the radius of curvature of the path of the particle before it is slowed down by the atmosphere. This expression treats the mesons as coming from outside the atmosphere. It also takes as the significant part of the deflection the additional deflection which the particle suffers because it loses energy in the atmosphere. Neglecting the term in $\frac{1}{\rho_0}$ would make a greater proportional difference at high energies where $\left(\frac{1}{\rho} - \frac{1}{\rho_0} \right)$ would be smaller in comparison with $\frac{1}{\rho}$ than at lower energies, and this would be in agreement with the trend in the numerical values. It appears from this that the expression used here would give a better

value of δ for use in estimating the asymmetry.

In the method used here it has been implicitly assumed that the path of the particle does not deviate very far from a straight line. We have in fact integrated the quantity $1/\rho$ along a straight line instead of along a slightly curved path. As the deflections are small, this would be a reasonable assumption in view of the accuracy required for the comparison of the asymmetry with the measured results.

CALCULATION OF THE ASYMMETRY.

As stated earlier we will calculate the asymmetry by considering the effect which the deflections of the mesons have on the symmetrical radiation which would exist in the absence of the magnetic field.

We will first describe the positive meson component of the undisturbed radiation.

Let $dN(E, \theta)$ be the number of positive particles with energies in the range $(E, E+dE)$ which would be counted in unit time by a telescope of small fixed aperture when pointed at an angular distance θ from the vertical in the east-west vertical plane.

Now

$$dN(E, \theta) = f(E, \theta) dN(E, 0). \quad . \quad . \quad . \quad . \quad (5.12)$$

and similarly

$$E^+ = \int_{E_1}^{\infty} f(E, \theta + \bar{\delta}(E, \theta)) N(E) dE \quad \dots \dots \dots (5.18)$$

We may put

$$W^+ = \int_{E_1}^{\infty} f(E, \theta) N(E) dE - \bar{\delta}(\theta) \frac{\partial}{\partial \theta} \int_{E_1}^{\infty} f(E, \theta) N(E) dE \quad \dots \dots \dots (5.19)$$

where $\bar{\delta}(\theta)$ has still to be determined. It will be shown later that if certain assumptions are made about the zenith dependence of different meson energy bands $\bar{\delta}(\theta)$ can be taken as the average value of the deflection taken over the energy spectrum.

Now it is well known experimentally (see, for example, Rogozinski and Voisin, 1949) that the total meson intensity varies with zenith angle very nearly as $\cos^Y \theta$ with Y approximately 2.2, although there is very little information available on how narrow energy bands vary. Thus, without detailed knowledge of $f(E, \theta)$, we can at any rate say that

$$\int_{E_1}^{\infty} f(E, \theta) N(E) dE = \cos^{2.2} \theta \int_{E_1}^{\infty} N(E) dE \quad \dots \dots \dots (5.20)$$

and therefore

$$\frac{\partial}{\partial \theta} \int_{E_1}^{\infty} f(E, \theta) N(E) dE = -2.2 \cos^{1.2} \theta \sin \theta \int_{E_1}^{\infty} N(E) dE \quad (5.21)$$

Substituting in equation (19), we obtain

$$W^+ = \left\{ \int_{E_1}^{\infty} N(E) dE \right\} \left\{ \cos^{2.2} \theta + 2.2 \bar{\delta}(\theta) \cos^{1.2} \theta \sin \theta \right\} \quad (5.22)$$

and similarly

$$E^+ = \left\{ \int_{E_1}^{\infty} N(E) dE \right\} \left\{ \cos^2 \theta - 2.2 \bar{\delta}(\theta) \cos^{1.2} \theta \sin \theta \right\} \quad (5.23)$$

The asymmetry of the positive radiation is now given by

$$\begin{aligned} A^+ &= 2(W^+ - E^+) / (W^+ + E^+) \\ &= 4.4 \bar{\delta}(\theta) \tan \theta \end{aligned} \quad (5.24)$$

It is still necessary to demonstrate the significance of $\bar{\delta}(\theta)$. To do this we will expand the right hand side of equation (5.17) in a different way. Using the first order Taylor series expansion of $f(E, \theta - \delta(E, \theta))$ we get

$$W^+ = \int_{E_1}^{\infty} \left\{ f(E, \theta) - \delta(E, \theta) f'(E, \theta) \right\} N(E) dE \quad (5.25)$$

where $f'(E, \theta) = \frac{\partial}{\partial \theta} f(E, \theta)$

therefore

$$W^+ = \int_{E_1}^{\infty} f(E, \theta) N(E) dE - \int_{E_1}^{\infty} \delta(E, \theta) f'(E, \theta) N(E) dE \quad (5.26)$$

Combining equations (5.19) and (5.26) gives

$$\bar{\delta}(\theta) \frac{\partial}{\partial \theta} \int_{E_1}^{\infty} f(E, \theta) N(E) dE = \int_{E_1}^{\infty} \delta(E, \theta) f'(E, \theta) N(E) dE$$

or
$$\bar{\delta}(\theta) = \frac{\int_{E_1}^{\infty} \delta(E, \theta) f'(E, \theta) N(E) dE}{\frac{\partial}{\partial \theta} \int_{E_1}^{\infty} f(E, \theta) N(E) dE} \quad (5.27)$$

The expression for $\bar{\delta}(\theta)$ would be difficult to evaluate, as it involves a detailed knowledge of $f(E, \theta)$ and $f'(E, \theta)$. If, however, we assume that the variation

of intensity with zenith angle is the same for all energies, i.e. that $f(E, \theta)$ is a function of θ only, then we can take $f'(E, \theta)$ and $f(E, \theta)$ outside the integral signs and cancel after differentiating in the denominator, which gives

$$\bar{\delta}(\theta) = \frac{\int_{E_1}^{\infty} \delta(E, \theta) N(E) dE}{\int_{E_1}^{\infty} N(E) dE} \quad \dots \quad (5.28)$$

which shows that in this case $\bar{\delta}(\theta)$ is the average of $\delta(E, \theta)$ taken over the energy spectrum (cf. Johnson's paper eq. 10).

The zenith dependence of the intensity of particles in small energy ranges is discussed by several authors (Kraushaar, 1949; Zar and Shamos, 1950; Rogozinski and Voisin, 1949.) The results indicate that the intensity of slow mesons with energy about 2×10^8 e.v. is approximately proportional to $\cos^3 \theta$, but for energies of 5.5×10^8 e.v. and greater the variation follows $\cos^{2.2} \theta$ fairly closely. The assumption of a $\cos^{2.2} \theta$ variation for all energies would introduce an error for only a small proportion of the mesons. In the absence of more detailed knowledge on this point, it is felt that the assumption is justified by the simplification which it leads to.

Rossi (1948) has given the differential range spectrum of vertically incident mesons at sea level, and this has been used in obtaining the values of $\bar{\delta}(\theta)$ for zenith angles of 15° , 30° , 45° and 60° , for lower limits of integration corresponding to 100 and 200 grams per square centimetre of air, which give approximately the lowest energies with which a meson could penetrate the telescopes with 12 and 25 centimetres of lead absorber between the counter trays. The values of $\bar{\delta}(\theta)$ are given in Table IV. From equation (5.24) the asymmetry of the purely positive or negative meson component has been calculated, and this is given in Table V. It has been assumed that the asymmetry of the positive and negative mesons is of the same magnitude; it is of course opposite in sign.

It should be noted that the same spectrum has been used for the calculation of $\bar{\delta}(\theta)$ for the different zenith angles. It has been necessary to do this in the absence of information for inclined directions. Practically all the experiments on the energy spectrum which the author has found in the literature have been made on the vertical or near vertical radiation, probably because of the greater counting rate for this direction. The assumption which was made that the zenith variation is the same

for all energies would lead to the same spectrum at different zenith angles since the intensity for all energies would be reduced in the same proportion. This would make the use of the vertical spectrum for the calculation of the mean deflection consistent. It is as well to bear in mind, however, that the situation could well be different from that assumed, especially for the larger zenith angles. The reliance which we can place on the theoretical asymmetry will be less in the case of the 45° and 60° values.

THE NETT ASYMMETRY OF THE MESON COMPONENT.

If there were equal numbers of positive and negative mesons in the radiation the asymmetry of the positive and negative components would cancel out, and no asymmetry of the two taken together would be observed. Since there are more positive than negative mesons, however, the asymmetry of the positive component predominates and an asymmetry of the same sign is observed for the total radiation.

In order to calculate the asymmetry of the total radiation once the asymmetry of the purely positive or negative components is known the positive excess, as it is called, has to be taken into account.

We take the quantity

$$p = 2(W^+ + E^+ - W^- - E^-) / (W^+ + E^+ + W^- + E^-) \quad . \quad . \quad . \quad (5.29)$$

as a measure of the positive excess.

The asymmetry of the positive and negative components is the same in magnitude but opposite in sign, therefore we may write

$$A = \frac{2(W^+ + W^- - E^+ - E^-)}{W^+ + W^- + E^+ + E^-} \quad . \quad . \quad . \quad (5.30)$$

The asymmetry of the total radiation is given by

$$\alpha = \frac{2(W^+ + W^- - E^+ - E^-)}{W^+ + W^- + E^+ + E^-} \quad . \quad . \quad . \quad (5.31)$$

Therefore from equations (5.29), (5.30) and (5.31),

$$\alpha = Ap/2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5.32)$$

The positive excess for the vertical direction has been studied by a number of workers, although very little has been done for inclined directions.

Direct measurements in the range of energies up to about 10^{10} e.v. have been made by Jones (1939) and Hughes (1940) using a cloud chamber in a magnetic field, determining the sign and energy of the particles by measuring the curvature of the tracks. Values of the positive to negative ratio of 1.29 and 1.21 respectively were obtained by these workers. Owen and Wilson (1949) using a magnetic spectrograph obtained a value of 1.268 ± 0.023 .

In their apparatus the trajectories of particles deflected by powerful electromagnets were traced by sets of geiger counters. All these workers found no significant variation of the ratio with energy.

Since the measurements of Owen and Wilson were made on a considerably greater number of particles than the others, and the value obtained lies between those of Hughes and Jones, the positive to negative ratio of 1.268 ± 0.023 has been used here.

Measurements of the positive excess by Bellario et al. (1948) led them to the conclusion that the positive excess decreases to about half its value between 0 and 60° zenith angle. In these experiments magnetised iron was used to deflect the particles, and as several corrections had to be applied to the results, the values of the positive excess would be less reliable than those obtained by the more straight forward methods. The positive to negative ratio will be taken as 1.268, and for a first comparison with the results will be assumed not to change with zenith angle.

Taking the positive to negative ratio as 1.268, we have

$$\begin{aligned} p &= \frac{2(W^+ + E^+ - W^- - E^-)}{W^+ + E^+ + W^- + E^-} \\ &= \frac{2(1.268 - 1)}{1.268 + 1} \\ &= 0.236 \end{aligned} \quad (5.33)$$

Using this value of p in equation (5.32) and the values of A given in Table V, the asymmetry of the total radiation given in Table VI has been obtained.

It should be pointed out here that an apparent slip has occurred in Johnson's treatment at this point. Referring to his paper, it can be seen that he takes a fraction f to be the fraction of the total radiation which consists of positives unbalanced by negatives. The author interprets this as

$$f = \frac{W^+ + E^+ - W^- - E^-}{W^+ + E^+ + W^- + E^-} \quad \dots \dots \dots (5.34)$$

so that

$$p = 2f \quad \dots \dots \dots (5.35)$$

$$\text{and } a = Af \quad \dots \dots \dots (5.36)$$

which is in agreement to this point. However, Johnson states that the observations of Hughes (1940) leads to the value 0.2 for f . Taking Hughes' positive to negative ratio of 1.21

$$\begin{aligned} f &= \frac{0.21}{2.21} \\ &= 0.095 \end{aligned}$$

Using the value 0.095 instead of 0.20 for f , Johnson's theoretical values are reduced by a little more than half. This would bring Johnson's theoretical curve into much better

agreement with the experimental results, as can be seen by referring to Figure 1 in the attached reprint of a paper published by Dr. Fenton and the author in 1948. The reduction of the theoretical values shown would have brought them near to the broken curve which was drawn to represent the empirical asymmetry.

PART VI.

COMPARISON OF THEORY AND EXPERIMENT.

We have seen in the introduction that the theory which explains the latitude effect and the low latitude east west asymmetry in terms of the allowed cones of primary cosmic ray particles of different energies gives the result that in latitudes where there is no latitude variation of the intensity the primary radiation should be isotropic above the atmosphere. Since the generally accepted position of the knee of the latitude effect is north of Hobart, it would be expected that the asymmetry of the primary radiation would be zero in this latitude (51.7° south geomagnetic.) It is therefore of interest that the results of the Hobart experiments show that an asymmetry exists at sea level. The experimental results have to be reconciled with the assumption that there are no field sensitive primaries by invoking a secondary radiation effect to explain the asymmetry. The theory originally given by T.H. Johnson (1941) has been revised and the asymmetry which would be expected to arise due to the deflection of secondary mesons in their flight through the atmosphere has been calculated. The experimental results are compared with the calculated values in Figures 25 and 26.

In Figure 25 the asymmetry is plotted against the thickness of lead absorber used in the apparatus for zenith angle settings of 45 and 60 degrees. The fact that the asymmetry is not greatly affected by the absorber supports the contention that the asymmetry is due to the deflections of the mesons, which make up the penetrating component. The slight increase observed when 12 centimetres are introduced is probably due to the elimination of a nearly symmetrical soft component, which would have the effect of diluting the asymmetry in measurements with no lead. The decrease between 12 and 24 centimetres can be attributed to the elimination of lower energy mesons, which, because of their greater deflection would contribute more to the asymmetry than higher energy mesons.

In comparing the zenith angle variation of the asymmetry (Fig. 26) with that given by the theory, it must be borne in mind that the calculated values are based on data which is more reliable for directions near the vertical than for inclined directions. Therefore it may be expected that if the theory gives a good account of the phenomena then the agreement will probably be best at the smaller zenith angles. In view of this the agreement found can be regarded as quite satisfactory.

Experimental results are available from Macquarie Island as well as Hobart. The geomagnetic latitude of the island station is 60.7° south, and should therefore be well beyond the knee of the latitude effect. These results show a definite asymmetry, which gives strong support to the assumption that the asymmetry in these latitudes is a secondary radiation effect. The values obtained at the two stations are nearly proportional to the strength of the horizontal magnetic field, which would be expected if the theory given in the text were valid. The ratio of the Hobart to Macquarie Island values averaged over all the settings used at both stations is found to be 1.59 ± 0.12 compared with the ratio of the horizontal component of the magnetic field, 1.46.

To obtain theoretical values with which to compare the Macquarie Island results, the values for Hobart have been reduced in proportion to the horizontal component of the magnetic field, for since the curvature of the path of a meson depends linearly on the magnetic field, so does the calculated asymmetry if all the other quantities used in the theory are assumed to be the same at both stations. Figure 27 shows the asymmetry measured at Macquarie Island with 12 centimetres of lead in the apparatus, and these are compared with the calculated values.

The points lie sufficiently close to the curve to show that the theory gives a good account of the asymmetry, at least up to zenith angles of between 60 and 70 degrees.

It can be seen in both cases that the experimental results indicate a falling off of the asymmetry at the greatest zenith angles used. Without experimental determinations closer to the horizon, however, this indication cannot be given very much weight. At Hobart it was not possible to make measurements at greater zenith angles than 60 degrees because of the prominence of Mt. Wellington in the western direction. Similar difficulties prevented the extension of the Macquarie Island experiments to any greater angle than 70 degrees.

CONCLUSION.

The results obtained in the Hobart experiments have been found to agree well with values of the asymmetry predicted by a form of Johnson's theory revised to include information on the energy spectrum and the positive excess of the meson component which has become available since the publication of Johnson's paper on this subject.

Comparison of the Hobart and Macquarie Island results further supports the theory by showing that the asymmetry at the two stations is proportional to the horizontal component of the earth's magnetic field, which is predicted by the theory.

We can now state the conclusion that the asymmetry in high latitudes can be satisfactorily accounted for as a secondary radiation effect. This removes the difficulty which arises because the theory of the geomagnetic effects based on the deflection of the primary cosmic ray particles in the earth's dipole field requires the east west effect to be zero in latitudes where the variation of the total cosmic ray intensity with latitude ceases, i.e., at latitudes above the knee of the latitude effect.

TABLE I.

Data obtained from Hobart experiments. The total number of counts recorded and the total recording time in hours (upper and lower numbers respectively) are given for each telescope.

DESCRIPTION OF RUN	TELESCOPE A.		TELESCOPE B.		SET USED. ^{1.}
	WEST	EAST.	WEST	EAST.	
60° No lead 8xii48-28ii49	58610 574	66164 661	64885 668	55336 582	D.T.I.
60° No lead 30vi48-5viii48	12667 119	12724 121	23420 239	22885 233	D.T.I.
60° No lead 24vi150-17viii50	63864 239	63732 239	69682 257	68274 258	D.T.M.
60° 12 cm. lead 5viii48-20xi48	33526 522	29797 478	31995 479	34054 523	D.T.I.
60° 12 cm. lead 17viii50-14ix50	40798 227	39530 226	20720 116	20346 116	D.T.M.
60° 24 cm. lead 28ii49-23vi49	49773 790	47387 775	43291 702	44237 723	D.T.I.

1. D.T.I. means First Double Telescope; D.T.M. means Modified Double Telescope.

TABLE I (Cont).

DESCRIPTION OF RUN	TELESCOPE A		TELESCOPE B		SET USED
	WEST	EAST	WEST	EAST	
45° no lead 22v150-3v1150	54144 110	52212 108	45268 92	45676 94	D.T.M.
45° 12 cm. lead 141x50-4x50	65808 194	64434 194	65287 194	64810 194	D.T.M.
45° 12 cm. lead 8151-161151	136920 403	131498 395	133986 395	133267 403	D.T.M.
45° 24 cm. lead 3v1150-24v1150	64498 199	62906 197	63770 197	63190 199	D.T.M.
30° 12 cm. lead 4x50-14x50	33679 67	34590 69	34476 69	32914 67	D.T.M.
15° 12 cm. lead 20x50-20x150	118819 185	115649 181	139531 218	141164 222	D.T.M.

TABLE II.

Residual air mass in grams per square centimetre for vertical and inclined paths.

Altitude (metres)	Residual air mass in path at x^0 .				
	$x = 0$	15	30	45	60
0	0	0	0	0	0
200	24.3	25.2	28.1	34.4	48.6
400	48.2	49.9	55.7	68.2	96.4
600	71.5	74.0	82.6	101	143
800	94.4	97.7	109	134	189
1000	117	121	135	165	234
1200	139	144	160	196	278
1400	160	166	185	227	321
1600	182	188	210	257	363
1800	202	210	234	286	405
2000	223	231	257	315	445
3000	319	330	368	450	637
4000	405	419	468	573	810
5000	483	500	557	683	965
6000	552	572	638	781	1100
7000	615	636	708	869	1230
8000	670	694	774	948	1340
9000	720	745	831	1020	1440
10000	764	791	882	1080	1530
11000	803	831	927	1140	1610
12000	836	866	965	1180	1670
13000	865	895	999	1220	1730
14000	889	921	1030	1260	1780
15000	910	942	1050	1290	1820
16000	928	961	1070	1310	1860
17000	943	977	1090	1330	1890
18000	956	990	1100	1350	1910

TABLE III.

Deflection δ in radians as a function of zenith angle and final residual range in air.

Residual range (gms/cm ²)	50	100	200	400	800	1500	3000	6000
Final energy/ moc ²	1.3	2.2	4.0	8.0	16.0	32.5	70	Approx. 140
Zenith angle								Approx.
15°	0.085	0.075	0.062	0.046	0.030	0.019	0.011	0.005
30°	0.090	0.078	0.065	0.048	0.034	0.021	0.012	Approx. 0.006
45°	0.092	0.082	0.069	0.054	0.037	0.023	0.014	Approx. 0.007
60°	0.104	0.089	0.076	0.060	0.044	0.030	0.019	Approx. 0.010

TABLE IV.

Average deflection $\bar{\delta}$ in radians as a function of zenith angle and low energy cutoff.

Zenith angle	15°	30°	45°	60°
Low energy cutoff, 2.2×10^8 e.v.	0.031	0.034	0.037	0.043
Low energy cutoff, 4.0×10^8 e.v.	0.028	0.031	0.034	0.040

TABLE V.

Asymmetry of purely positive or negative component as a function of zenith angle and low energy cutoff.

Zenith angle =	15°	30°	45°	60°
Low energy cutoff 2.2x10 ⁸ e.v.	0.0365	0.0864	0.1628	0.3277
Low energy cutoff 4.0x10 ⁸ e.v.	0.0330	0.0788	0.1496	0.3048

TABLE VI.

Asymmetry of total radiation as a function of zenith angle
and low energy cutoff.

Zenith angle =	15°	30°	45°	60°
Low energy cutoff 2.2x10 ⁸ e.v.	0.0043	0.0102	0.0192	0.0387
Low energy cutoff 4.0x10 ⁸ e.v.	0.0039	0.0092	0.0177	0.0360

TABLE VII.

Measured asymmetry for different lead thicknesses
and zenith angles.

Zenith angle =	15°	30°	45°	60°
No Lead			0.0175±0.0035	0.0168±0.0020
12 cms. Lead	0.0066±0.0021	0.0113±0.0042	0.0245±0.0019	0.0303±0.0032
24 cms. Lead			0.0213±0.0034	0.0197±0.0031

TABLE VIII.

Comparison of Hobart and Macquarie Island asymmetry.

Description	Hobart	M/I	H/(M/I) = \bar{x}
15° 12 cm. lead	0.0066±0.0021	0.0060±0.0029	1.10
30° 12 cm. lead	0.0113±0.0042	0.0049±0.0042	2.31
45° no lead	0.0175±0.0035	0.0104±0.0037	1.68
45° 12 cm. lead	0.0245±0.0019	0.0139±0.0025	1.76
45° 24 cm. lead	0.0213±0.0034	0.0107±0.0053	1.99
60° no lead	0.0168±0.0020	0.0144±0.0043	1.17
60° 12 cm. lead	0.0303±0.0032	0.0265±0.0052	1.14
60° 24 cm. lead	0.0197±0.0031		
70° 12 cm. lead		0.0277±0.0110	

$$\bar{x} = 1.59 \pm 0.12$$

Ratio of horizontal component of magnetic field at
Hobart and Macquarie = 19/13 = 1.46.

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Measurements of the East-West Asymmetry of Cosmic Rays at Hobart, Tasmania

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Measurements of the high latitude asymmetry of cosmic rays have been made at Hobart in geomagnetic latitude 51.7° south. A Geiger counter telescope has been used at a zenith angle of 45° with and without 12.5 cm of lead absorber. The asymmetry is increased by a factor just over two when the lead is used. The increase indicates that the hard component of the radiation is responsible for the high latitude asymmetry, and the magnitude of the increase suggests a preferential absorption of negative particles by the lead.

I. INTRODUCTION

THE east-west asymmetry in cosmic-ray intensity observed at latitudes below the knee of the latitude intensity curve, i.e., below about $40-45^\circ$ geomagnetic latitude, is explained by the deflections of the primary particles in the earth's magnetic field and the excess of positive primary particles, but should disappear at higher latitudes, where field sensitive primaries do not contribute appreciably to the radiation at sea level. A small asymmetry has been observed, however, at higher latitudes¹⁻⁵ and T. H. Johnson⁶ has given a theory to account for this in terms of the deflection of the secondary penetrating particles while they are being slowed down by ionization in the atmosphere. Data obtained by T. H. Johnson⁶ and F. G. P. Seidl¹ between 49° and 54° north geomagnetic latitude support the theory, but the probable errors of some of their results have been too large to test the theory adequately. Experiments have therefore been undertaken here to add to the data of the above workers. The apparatus has been running for some months and some significant results are already available.

The asymmetry is usually given as

$$A = (j_w - j_e) / \frac{1}{2}(j_w + j_e).$$

Values of the order of 0.01 have been found at

high latitudes by Seidl, Johnson, and ourselves, compared with values more than ten times as large found near the magnetic equator.

II. APPARATUS

Six Geiger counters are used in two banks of three to form a telescope which is mounted in a yoke supported on a turntable. The telescope can be rotated round a horizontal axis to set the zenith angle, and the turntable rotated to obtain the azimuth setting. The axis of the turntable is set within one minute of arc of the vertical, making the zenith angle reproducible after each rotation with this accuracy, and the azimuth setting, which is maintained after each rotation by stops on the turntable, is accurate to within 1° .

The telescope has a sensitive solid angle extending nearly 17° either side of the zenith setting and about 25° either way in the direction perpendicular to this.

The two banks of counters are connected through a coincidence amplifier to a multi-vibrator which drives a post office call meter. The call meter, and electric clock, a barometer, and an "east-west" indicator are photographed by a 16-mm camera at intervals of four hours. The camera is controlled by a timing unit which also controls the rotation of the turntable from one setting to the other.

Use has been made of voltage regulator tubes to stabilize the various working voltages, and in particular the high voltage supply for the counter tubes uses a series of VR tubes in cascade, the working voltages being tapped from between the tubes or from potential dividers across the tubes.

The functioning of the coincidence circuit is

¹ F. G. P. Seidl, *Phys. Rev.* **59**, 7 (1941).
² T. H. Johnson and E. C. Stevenson, *Phys. Rev.* **44**, 125 (1933).
³ E. C. Stevenson, *Phys. Rev.* **44**, 855 (1933).
⁴ J. C. Stearns and R. C. Bennett, *Phys. Rev.* **43**, 1038 (1933).
⁵ J. C. Stearns and D. K. Froman, *Phys. Rev.* **46**, 535 (1934).
⁶ T. H. Johnson, *Phys. Rev.* **59**, 11 (1941).

TABLE I.

No lead	West	East	Average rate
Total counts	158,782	158,875	
Total time	888.67471 hr.	896.30249 hr.	
Cts/hr.	178.67 ± 0.302	177.25 ± 0.300	177.96 ± 0.21
$A = (j_w - j_e) / \frac{1}{2}(j_w + j_e) = 0.00797 \pm 0.00239$			

tested by connecting the two inputs to the X and Y plates of a cathode-ray oscillograph. The separate pulses show as X or Y pips, and a coincidence shows as a pip at 45° . These can be checked against the clicks of the recorder. The coincidence circuit has been tested regularly in this way, and has had to be adjusted to compensate for a slight loss in efficiency on only two or three occasions.

The whole apparatus is housed in a shed built of "Masonite" sheets, situated away from neighboring buildings.

III. COMPUTATION OF THE RESULTS

Data have been obtained by running the telescope alternately in easterly and westerly directions for about four-hourly periods. Because of a slight variation in the timing unit the schedule of the runs tends to precess around the clock, and it has been assumed that this would cause any effect due to a daily variation in the intensity to cancel out over a period. It has also been assumed that, averaged over the time of

TABLE II.

12.5 cm lead	West	East	Average rate
Total counts	57,491	65,117	
Total time	374.78250 hr.	432.75555 hr.	
Cts/hr.	153.39 ± 0.432	150.47 ± 0.397	151.93 ± 0.29
$A = 0.0192 \pm 0.0038$			

operation of the apparatus, effects caused by variation of the barometric pressure, changes in the efficiency of the recording circuit, accidental coincidences, and shower coincidences would be small and affect the counting rates from the two directions equally, not influencing the final result very much.

The total counts and total times pertaining to each direction have been used in computing the counting rates, the probable errors of which have been taken as $\pm 0.6745 j / N^{\frac{1}{2}}$, where N is the number of counts used to obtain j . The probable errors of the asymmetry have been calculated from those of the counting rates.

The data and the results obtained from them are tabulated in Tables I and II. Table II contains those for the period when 12.5 cm of lead were placed between the two banks of counters to absorb the soft component of the radiation. In Fig. 1 these results are shown added to those of Seidl¹ and Johnson.⁶

IV. DISCUSSION

The increase in the asymmetry observed when lead absorber is used agrees with Seidl's observation.¹ The existence of the increase supports the supposition that the asymmetry in these latitudes is due to the hard component of the radiation, but the increase is greater than would be expected if the function of the lead were only to cut out a symmetrical soft component. If we take the intensity of the soft component in our observations to be 26.03 counts per hour (i.e., the difference between the average intensities in the two sets of results) and compute the asymmetry of the hard component by correcting the "no lead" results we find that $A = 0.0095$, which is appreciably less than the value observed with the lead absorber. Thus it appears that the lead has enhanced the asymmetry by absorbing more of the radiation when the apparatus faced east than when it faced west. Seidl¹ has suggested that the increase in the observed asymmetry may be

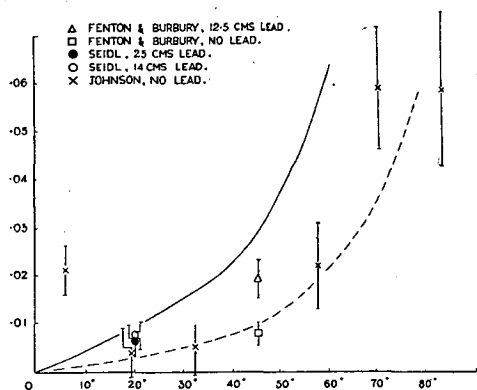


FIG. 1. The high latitude asymmetry of cosmic rays at sea level plotted against the zenith angle. The solid curve gives the values for the hard component of the radiation predicted by Johnson's theory,⁶ assuming an energy distribution of mesons proportional to E^{-2} and a lower energy limit of 2.2×10^8 ev. The broken curve is drawn through the "no lead" values (except that for small zenith angle) and represents the empirical asymmetry of the total radiation, i.e., the hard and soft components taken together.

due to a preferential absorption of the negative mesons by the lead, and the present results are in accord with this hypothesis.

If the assumption that the soft component is symmetrical be accepted as true, then the asymmetry of the hard component arriving at the apparatus should be given by calculation from the "no lead" measurements, and in view of the evidence that an absorber influences the results we are of the opinion that this procedure gives a more reliable value than that obtained directly. It is to be noted that this would give values falling on a curve slightly above the broken curve in the figure, and appreciably below the values predicted by Johnson's theory (the solid curve) for a lower energy limit of 2×10^8 ev.

From the data at present available it appears that Johnson's theory gives the form of the asymmetry *vs.* zenith angle curve but the values

are slightly large. Further experiments are being conducted, and it may be possible to suggest some modification of the theory when more results are available.

ACKNOWLEDGMENTS

The authors have pleasure in expressing their sincere thanks to Professor A. L. McAulay for his ready advice and for stimulating discussions during the course of the work. We are very grateful to the Electrolytic Zinc Company, Ridson, Tasmania, for a grant for apparatus and to the C.S.I.R. for a grant which enabled one of us (D.W.P.B.) to take part in this research. It is a pleasure to acknowledge the encouragement received from Dr. T. H. Johnson when we first proposed to conduct these experiments. We would also like to thank Mr. R. L. Propsting for his enthusiastic help in the construction of the apparatus.

The East-West Asymmetry of the Cosmic Radiation in High Latitudes and the Excess of Positive Mesotrons

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The slight east-west asymmetry of the cosmic radiation in high latitudes, now confirmed by Seidl, is interpreted to be the result of the deflection by the earth's magnetic field of the mesotron component while the rays are losing energy by ionization in the atmosphere. Since this component contains about twenty percent more positive than negative rays these deflections result in an asymmetry. Orbits of rays, including those in the range of energy where rest mass cannot be neglected, have been investigated and the deflections determined. It is assumed that deflections without energy loss, namely, those of the primary rays described by the theory of Lemaitre and Vallarta, result in a symmetrical distribution for the energy

ranges concerned. The asymmetry is traced to the difference between the actual deflection and that of a ray which loses no energy. The "difference" deflection δ shifts the angular distribution so that rays which, in the absence of a field, would have produced an intensity proportional to $\cos^2 \zeta$ at zenith angle ζ actually produce this intensity at an angle $\zeta + \delta$. Asymmetries calculated in this way agree with the observed values, and give the correct variation of asymmetry with zenith angle and elevation. Although the data are meager, the theory seems to be in accord with the existing evidence regarding the effect of absorbing material upon the asymmetry.

INTRODUCTION

IT is now recognized that the east-west asymmetry of the cosmic radiation occurring in the equatorial zone is produced by the deflection of primary cosmic rays before their entry into the earth's atmosphere, and that it arises from an excess of positive particles in that part of the primary radiation responsible for the intensity in the lower part of the atmosphere. These primary deflections, however, do not explain the slight asymmetry observed in high latitudes nor the comparatively large asymmetries noted at zenith angles near the horizon within the equatorial belt. Since the slight increase of cosmic-ray intensity with latitude at latitudes above the so-called knee of the latitude effect has now been explained as a temperature effect,¹ it is probable that no rays in the field sensitive range of energy at these high latitudes make their effects felt at sea level. It has been shown by Lemaitre and Vallarta that rays of energy greater than the field sensitive range, the only rays whose effects are felt at sea level in high latitudes, are incident uniformly from all directions, and the high latitude asymmetry cannot be traced to the deflections of the primary rays themselves. But as rays lose energy in the atmosphere, they are deflected by the magnetic field from their primary

orbits. Since the observations of Hughes and others² have shown the presence in the atmosphere of about twenty percent more positive than negative mesotrons, these deflections produce an asymmetry in the angular distribution.

Deflections of this type have been discussed by Bowen³ and by Rossi⁴ who have shown that no appreciable part of the equatorial asymmetry can be explained in this way, but it appears from the present treatment that this effect can account for the high latitude asymmetry and for the asymmetries at large zenith angles in the equatorial belt. Since we now have a considerably greater knowledge of the behavior and the composition of the cosmic radiation than was available at the time of the former discussions of this effect, the present treatment is somewhat different from those of the above authors.

The first evidence of an east-west effect was observed by Johnson and Street⁵ on the summit of Mount Washington, New Hampshire, geomagnetic latitude 56° , considerably above the knee of the latitude effect which recent investigations have placed at about the latitude of 40° .

² D. J. Hughes, *Phys. Rev.* **57**, 592 (1940); P. M. S. Blackett, *Proc. Roy. Soc. A* **159**, 1 (1937); L. Leprince-Ringuet and J. Crussard, *J. de phys. et rad.* **8**, 207 (1937).

³ I. S. Bowen, *Phys. Rev.* **45**, 349 (1934).

⁴ B. Rossi, *Rendi Lincei* **15**, 62 (1932).

⁵ T. H. Johnson, *J. Frank. Inst.* **214**, 665 (1932); T. H. Johnson and J. C. Street, *Phys. Rev.* **43**, 381 (1933).

¹ A. H. Compton and R. N. Turner, *Phys. Rev.* **52**, 799 (1937); P. M. S. Blackett, *ibid.* **54**, 973 (1938).

Later and more accurate measurements in Pennsylvania and in Colorado by Johnson and Stevenson⁶ and by Stearns and Froman⁷ have confirmed the existence of a high latitude asymmetry and have shown that it amounts to about one percent at 30° from the zenith, probably increasing to about five percent at 60°. The effect is almost independent of elevation up to the summit of Mount Evans, 14,000 feet above sea level. In a recent extended series of observations, carried out at Troy, New York, 54° N geomagnetic latitude, Seidl⁸ has measured the asymmetry at an average zenith angle of 20° and has shown that it is not much affected by lead absorbing screens up to 25 cm thick, but probably diminishes slightly with increase of lead thickness. In the equatorial belt the writer⁶ has noted an indication of an abnormally high asymmetry close to the horizon where the normal asymmetry should disappear because of atmospheric absorption.

In order to account for these effects, we assume that the rays reaching sea level are

symmetrically distributed upon their arrival at the top of the atmosphere or at the point where they are produced as secondaries of such symmetrically distributed primary radiation, but as the rays are slowed down by atmospheric ionization their paths become more and more curved and when they have reached the observer they have experienced a slight deflection from their original direction or the direction they would have had in the absence of energy losses. Any unbalance in the numbers of positives and negatives results in an asymmetry, for if the average deflection is δ , the intensity at zenith angle $\zeta + \delta$ corresponds to that occurring at angle ζ in the symmetrical distribution. The deflection is toward the west for positive rays and towards the east for negatives. When treated in this way it becomes unnecessary to consider the details of atmospheric absorption or of the instability of the mesotron, for the influence of these phenomena upon the probability that a ray will arrive at sea level from the direction concerned is already taken into account in determining the normal symmetric distribution.

THEORY OF THE DEFLECTIONS

Since we are concerned with an explanation of the east-west asymmetry, we will consider rays whose orbits lie in the east-west vertical plane. In calculating the deflection suffered by a cosmic ray during its trip through the atmosphere, the approximation will be used that the rate of loss of energy by ionization is independent of the energy and is equal to $\alpha m_0 c^2$ per cm of air at a pressure of one atmosphere. This approximation is accurate within a few percent for mesotron energies greater than about ten million volts and is expressed by

$$d\epsilon/ds = \alpha p, \quad (1)$$

where p is the pressure in atmospheres, s is the orbital distance measured backwards along the orbit from the position of the observer, and $\epsilon m_0 c^2$ is the energy of the ray, i.e., $\epsilon = (1 - \beta^2)^{-1/2} - 1$. The radius of curvature of the ray in the earth's field, whose horizontal component is H , is given by

$$\rho = R(\epsilon^2 + 2\epsilon)^{1/2}, \quad (2)$$

where R stands for the quantity $m_0 c^2 / eH$.

The variation of ρ with orbital distance is then given by

$$d\rho/ds = (d\rho/d\epsilon)(d\epsilon/ds) = \alpha R p (\epsilon + 1) (\epsilon^2 + 2\epsilon)^{-1/2} \quad (3)$$

or by making use of Eq. (2)

$$d\rho/ds = \alpha R p (1 + R^2/\rho^2)^{1/2}. \quad (4)$$

⁶ T. H. Johnson, Phys. Rev. **48**, 287 (1935); T. H. Johnson and E. C. Stevenson, *ibid.* **44**, 125 (1933).

⁷ D. K. Froman and J. C. Stearns, Phys. Rev. **46**, 535 (1934).

⁸ F. G. P. Seidl, Phys. Rev. **59**, 7 (1941), preceding paper.

TABLE I. The atmospheric deflection δ , expressed in radians, for mesotrons of various energies as a function of the zenith angle of the orbits and the elevation of the observer.

FINAL ENERGY EV $\times 10^{-8}$	0	1	2	4	8	15	30	60
Sea level								
$\zeta = 0^\circ$	0.077	0.049	0.039	0.028	0.017	0.010	0.0041	0.0015
20°	0.079	0.050	0.040	0.030	0.018	0.0105	0.0047	0.0017
40°	0.083	0.054	0.045	0.033	0.022	0.0141	0.0060	0.0024
60°	0.093	0.063	0.054	0.042	0.030	0.0195	0.010	0.0044
Alt. 4300 m								
$\zeta = 20^\circ$	0.11	0.064	0.049	0.032	0.019	0.0095	0.0036	0.0012
40°	0.12	0.073	0.057	0.040	0.023	0.012	0.0049	0.0017
60°	0.13	0.080	0.069	0.052	0.033	0.019	0.0086	0.0034

If h_0 is the extent of the homogeneous atmosphere, the pressure at any height x above sea level is given approximately by $p = \exp(-x/h_0)$. Since, as the calculation will show, the maximum deflection does not exceed a few degrees, x may be replaced by $x_0 + s \cos \zeta$ where ζ is the zenith angle of the ray when it reaches the observer, and x_0 is the height above sea level of the observer. Then Eq. (4) may be written

$$d\rho/ds = \alpha R(1 + R^2/\rho^2)^{1/2} \exp [(-x_0 - s \cos \zeta)/h_0]. \quad (5)$$

The integral of (5) is

$$\rho = [(a - be^{-\gamma s})^2 - R^2]^{1/2}, \quad (6)$$

where $a = [\rho_0^2 + R^2]^{1/2}$, ρ_0 is the initial radius of curvature of the ray upon its entry into the atmosphere at a height considered to be great compared with h_0 but small compared with the radius of the earth, b is R times the energy, expressed in units of $m_0 c^2$, of a ray just able to penetrate from the top of the atmosphere to the observer, i.e.,

$$b = \alpha R h_0 \sec \zeta \exp(-x_0/h_0) \quad \text{and} \quad \gamma = (\cos \zeta)/h_0.$$

Writing $z = be^{-\gamma s}/a$ and $k = R/a$, the deflection of a ray during its passage through the atmosphere is

$$\theta = \int_{s=0}^{s_1} ds/\rho = -(1/\gamma a) \int_{z=b/a}^{(b/a) \exp(-\gamma s_1)} [z^{-1}(z^2 - 2z + 1 - k^2)^{-1/2}] dz, \quad (7)$$

where s_1 is some distance, large compared with $h_0 \sec \zeta$ but small compared with the radius of the earth. On integrating Eq. (7) and putting in the limits, the total deflection is

$$\theta = (1/\gamma a)(1 - k^2)^{-1/2} \{ \log [\{ 1 - (b/a)e^{-\gamma s_1} \}^2 - k^2]^{1/2} + (1 - k^2)^{1/2} - (b/a)e^{-\gamma s_1}(1 - k^2)^{-1/2}] \\ - \log [\{ 1 - (b/a) \}^2 - k^2]^{1/2} + (1 - k^2)^{1/2} - (b/a)(1 - k^2)^{-1/2}] \} + (s_1/a)(1 - k^2)^{-1/2}. \quad (8)$$

The last term of Eq. (8) is the deflection

$$\theta_0 = \int_{s=0}^{s_1} \frac{ds}{\rho_0},$$

which the ray would have experienced over the same path if no energy had been lost by atmospheric ionization, a deflection which we assume would have resulted in a symmetric distribution at sea level. The increased deflection resulting from atmospheric energy losses is then $(\theta - \theta_0)$ and in the limit ($s_1 = \infty$) this converges to

$$\delta = \lim_{s_1 \rightarrow \infty} (\theta - \theta_0) = \frac{1}{\gamma a(1 - k^2)^{1/2}} \log \frac{2}{1 - \frac{b}{a(1 - k^2)} + \left[\frac{(1 - b/a)^2 - k^2}{1 - k^2} \right]^{1/2}}. \quad (9)$$

The deflections calculated from Eq. (9) for mesotrons reaching the observer from various zenith angles at sea level and at 4300 m elevation are shown as a function of the final energy in Table I. In making these calculations the following values of the constants have been used: $\alpha = 2.5 \times 10^{-6}$, corresponding to a mass energy of the mesotron of 10^8 electron volts, and an ionization loss of 2500 volts per cm at normal atmospheric pressure; $H = 0.18$ c.g.s. unit, the value of the horizontal component of the earth's field at Troy; $h_0 = 8.0 \times 10^5$ cm; $R = 18.5 \times 10^5$ cm.

It is an interesting feature of this form of the theory that a ray is completely stopped before it has been deflected through a very large angle. For example, a ray with initial radius of curvature $\rho_0 = (b^2 + 2bR)^{1/2}$, having just enough energy to reach sea level along the orbit inclined at angle ζ from the zenith, is deviated by only $4^\circ 21'$ at $\zeta = 0^\circ$.

CALCULATION OF THE ASYMMETRY

Since the deflection is a function of the final energy of the ray, the average deflection depends upon the energy distribution of the radiation at sea level. Studies of the magnetic bending of cosmic rays in the cloud chamber⁹ have shown this distribution to be of the form

$$N(E)dE = (A/E^n)dE, \quad \text{with } n \text{ about } 3.$$

The average deflection is then

$$\bar{\delta} = (n-1)E_1^{n-1} \int_{E_1}^{\infty} [\delta(E)/E^n] dE, \quad (10)$$

where the limit E_1 of the integral corresponds to the stopping power of the instrument, or, if no absorber is used in the instrument, this limit is about 2×10^8 electron volts below which it has been found⁹ that very few mesotrons are present in the atmosphere. In Seidl's apparatus two thicknesses of lead shields have been used, one 14.5 cm thick and the other 25 cm thick, whereas in the experiments of the writer and in one of Seidl's experiments no lead was used. Corresponding to these thicknesses the low energy limits are 2.2×10^8 electron volts and 3.5×10^8 electron volts, respectively. The values of $\bar{\delta}$ calculated from Eq. (10) are shown in Table II.

If the positive or the negative rays are considered alone, the first-order effect of these

TABLE II. Values of the average deflection $\bar{\delta}$ in radians.

LOW ENERGY LIMIT	SEA LEVEL			4300 METERS		
	$\zeta = 20^\circ$	40°	60°	20°	40°	60°
$E_1 = 2.2 \times 10^8$ ev	0.031	0.033	0.045	0.034	0.043	0.054
$E_1 = 3.5 \times 10^8$ ev	0.023	0.024	0.030	0.023	0.029	0.042

⁹ P. M. S. Blackett, Proc. Roy. Soc. A159, 1 (1937).

deflections is to shift the angular distribution through the angle $\bar{\delta}$. The intensity which in the absence of this phenomenon would have appeared at any zenith angle ζ will actually be found at the angle $\zeta + \bar{\delta}$. Since the length of the path through the atmosphere is not greatly altered by these deflections, it is not necessary to bring into consideration phenomena which affect the probability that a ray will reach sea level along a given orbit, for these phenomena are operative in determining the normal angular distribution of the radiation. To a close approximation this distribution is given by

$$j(\zeta) = j_0 \cos^2 \zeta. \quad (11)$$

Hence, the difference of the intensities on the two sides of the zenith at angle ζ is

$$j(\zeta + \bar{\delta}) - j(\zeta - \bar{\delta}) = 2\bar{\delta}(dj/d\zeta) = 4\bar{\delta}j(\zeta) \tan \zeta.$$

The asymmetry, then, of the purely positive or of the purely negative component is

$$\alpha = 2(j_w - j_e)/(j_w + j_e) = 4\bar{\delta} \tan \zeta.$$

If, on the other hand, a fraction f of the total radiation consists of positives unbalanced by negatives, the asymmetry will have the value

$$\alpha = 4f\bar{\delta} \tan \zeta.$$

The observations of Hughes indicate that $f = 0.20$, there being more positives than negatives. With this value of f the calculated values of the asym-

TABLE III. Calculated values of the asymmetry at various zenith angles and altitudes for two lead thicknesses.

LOW ENERGY LIMIT	SEA LEVEL			4300 METERS		
	$\zeta = 20^\circ$	40°	60°	20°	40°	60°
$E_1 = 2.2 \times 10^8$ ev	0.0089	0.022	0.061	0.010	0.029	0.075
$E_1 = 3.5 \times 10^8$ ev	0.0065	0.015	0.043	0.007	0.020	0.058

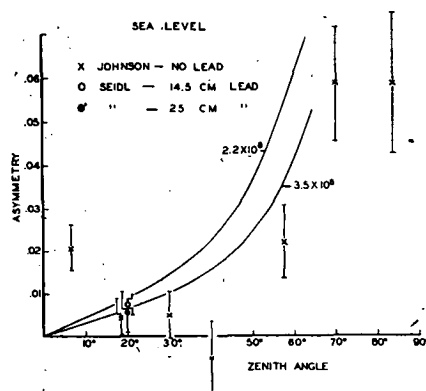


FIG. 1. The high latitude asymmetry at sea level, plotted against zenith angle. The curves show the theoretical values based upon an energy distribution proportional to E^{-2} , with lower limits at 2.2×10^8 electron volts and at 3.5×10^8 electron volts, corresponding respectively to lead absorber thicknesses of 14.5 cm and 25 cm. The points represent the experimental values obtained by Seidl and Johnson.

metry for the two lead thicknesses are given in Table III. Figures 1 and 2 show the variations of the asymmetry with zenith angle at the two elevations. The curves represent the calculated values, while the points indicate the values found by Seidl and the writer. In every case the probable errors are large, but there seems to be some justification for the belief that the theory gives an adequate representation of the data, both as regards the magnitude of the asymmetry and its variations with zenith angle and thickness of lead absorber. The theory gives a somewhat larger asymmetry than is observed near the horizon, especially at the higher elevation. This may indicate that the predominance of the positive component is not as pronounced at the higher elevations as that corresponding to the value $f=0.20$. This could be explained by the presence at the higher elevations of a larger fraction of soft component rays consisting of equal numbers of positive and negative electrons.

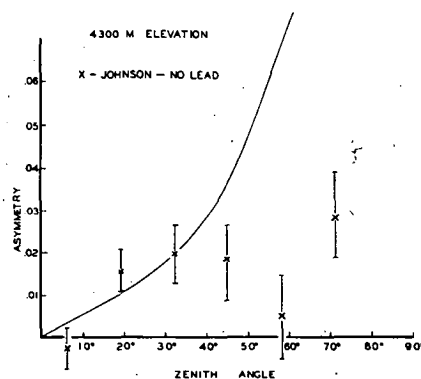


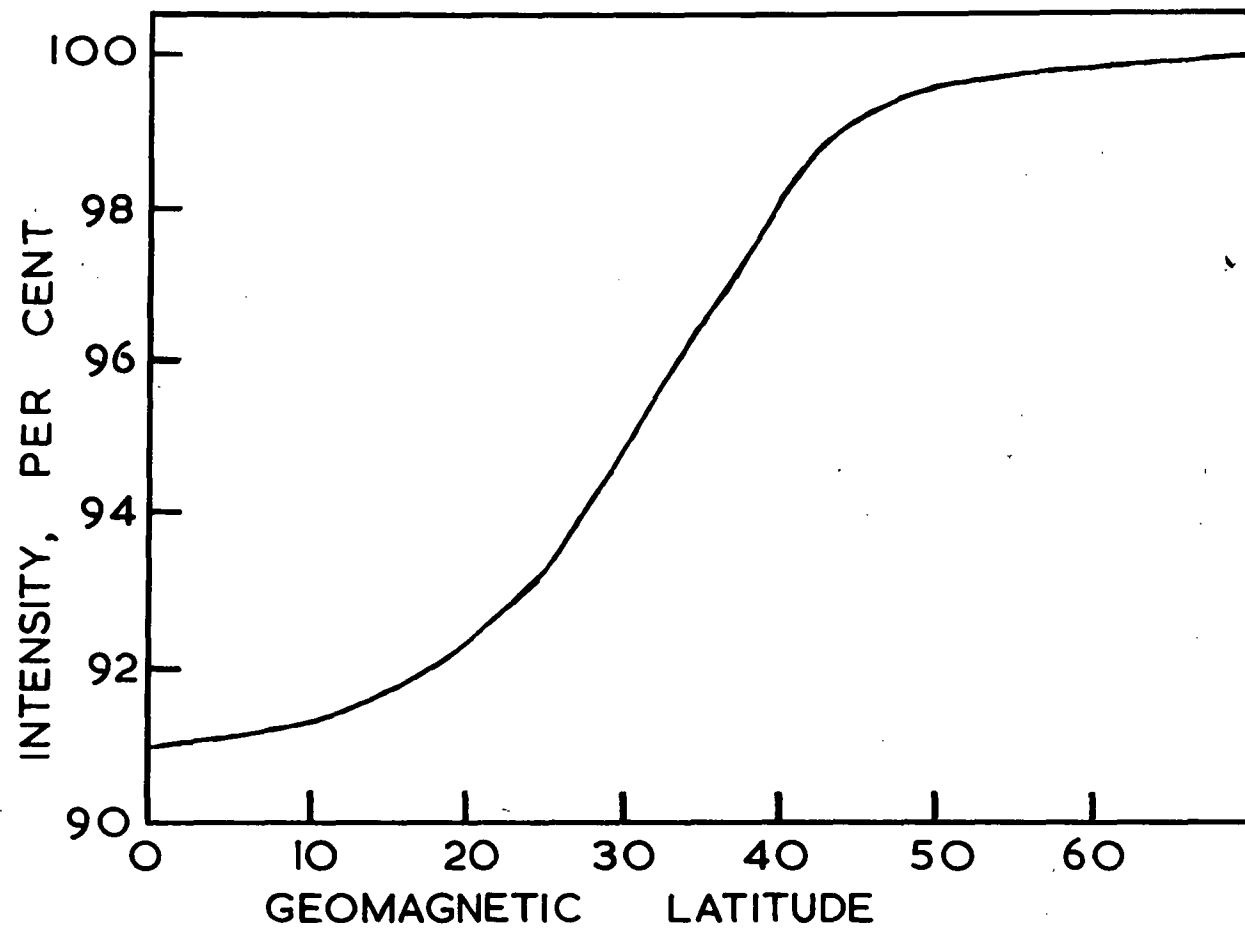
FIG. 2. The high latitude asymmetry at an elevation of 4300 meters above sea level (0.6 atmosphere). The curve shows the theoretical values based upon an E^{-2} distribution with a lower energy limit at 2.2×10^8 electron volts.

It may also be noted that Blackett¹⁰ in a more recent paper points out that the spectrum is nearly constant for energies less than 10^9 volts and at higher energies it falls off as E^{-2} or a little faster. An energy distribution of this type would give a higher average energy than that of the E^{-2} distribution upon which the calculations have been based, and a consequent lower asymmetry. Thus it seems possible to bring the theory into better accord with the asymmetry at zenith angles close to the horizon without disturbing its agreement with the data at higher angles at sea level. At the higher elevation, however, it would be necessary to invoke some asymmetry of the primary rays to explain the apparent peak at 30° . Such an assumption would not necessarily be out of harmony with other facts for the knee of the latitude effect may well lie above 51° at that elevation.

In conclusion, the writer takes pleasure in acknowledging several stimulating discussions of this problem with Mr. F. G. P. Seidl who has contributed essential elements in its final formulation.

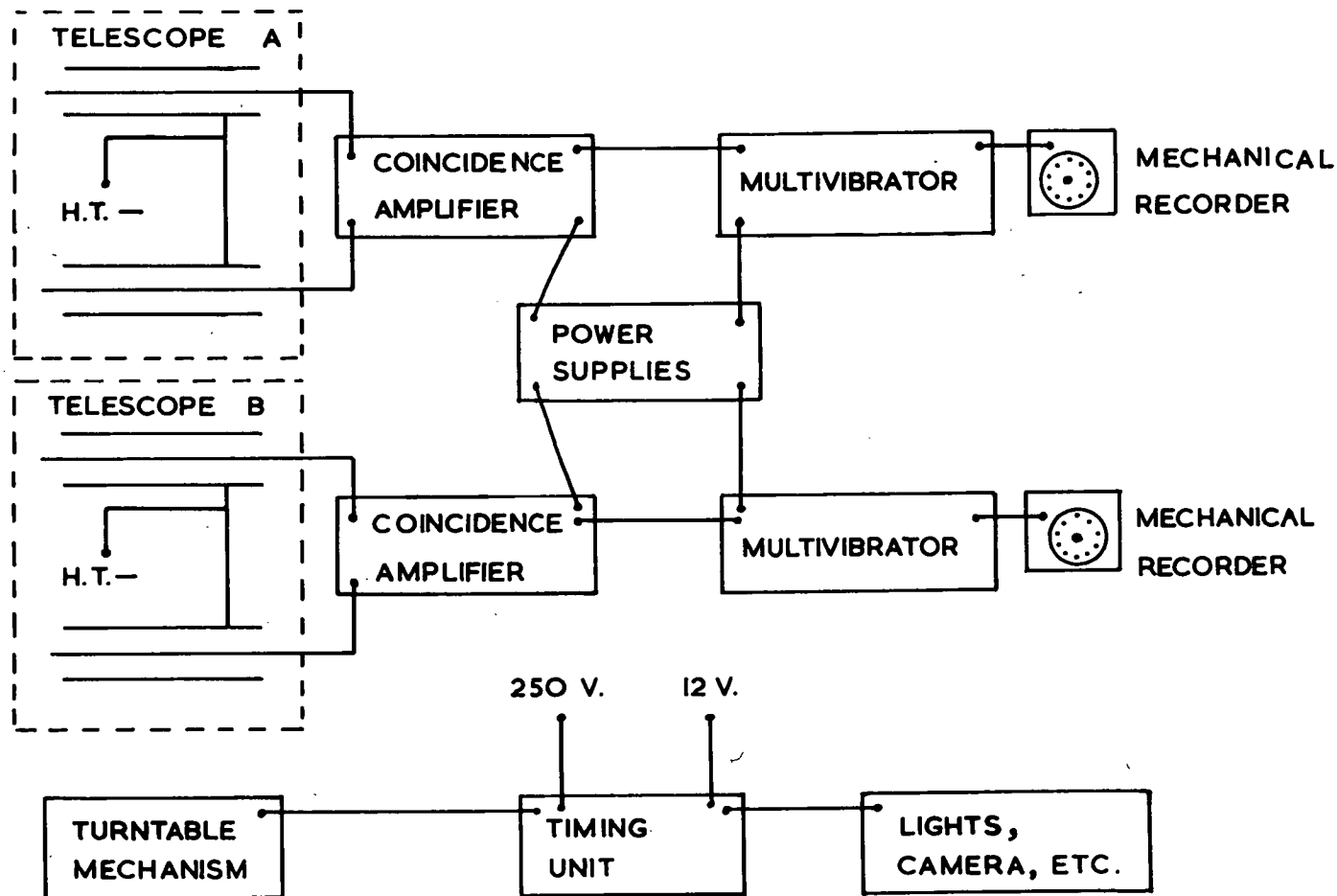
¹⁰ P. M. S. Blackett, Proc. Roy. Soc. A165, 11 (1938).

Figure 1 - Graph of the sea-level cosmic ray intensity against geomagnetic latitudes. The intensity shown includes rays from all directions which can penetrate 12 cm. lead.



LATITUDE VARIATION OF COSMIC RAY INTENSITY.

Figure 2 - Block diagram showing the components of the
Double Telescope Apparatus described in Part I.



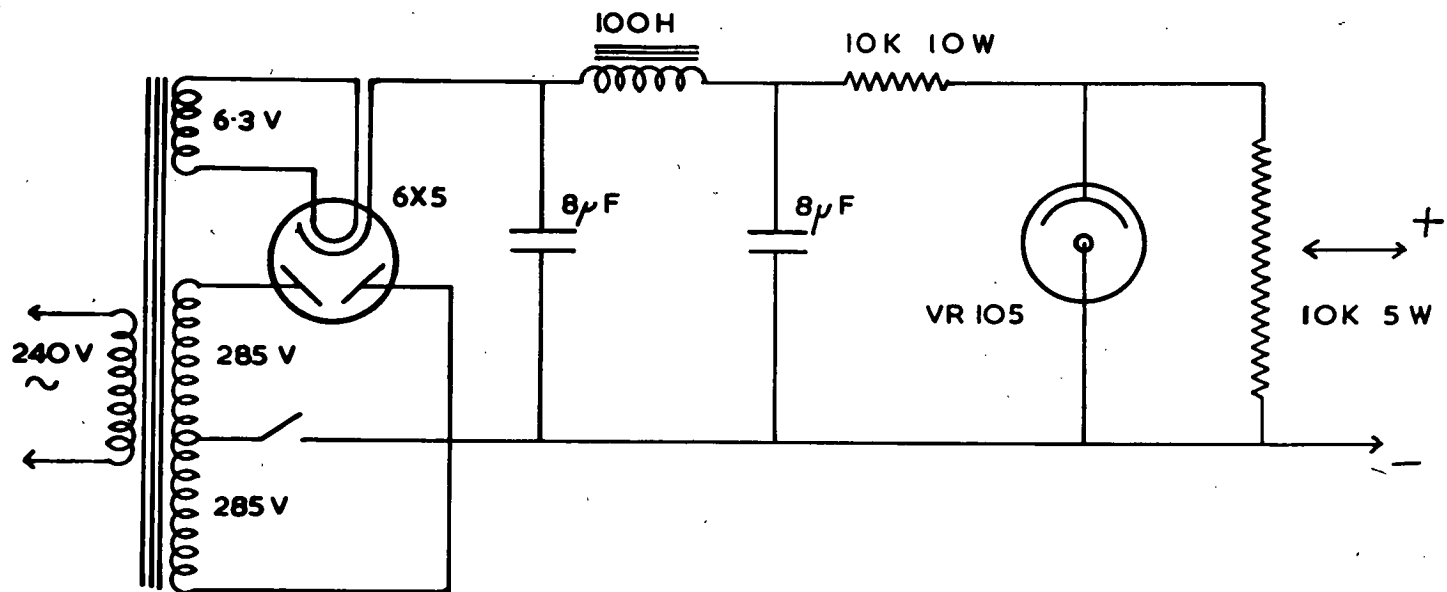
LAYOUT OF DOUBLE TELESCOPE ASYMMETRY APPARATUS.

Figure 3 - Circuit of high tension power supply used in the experiments. Stabilisation is obtained by the use of voltage regulator tubes in cascade.



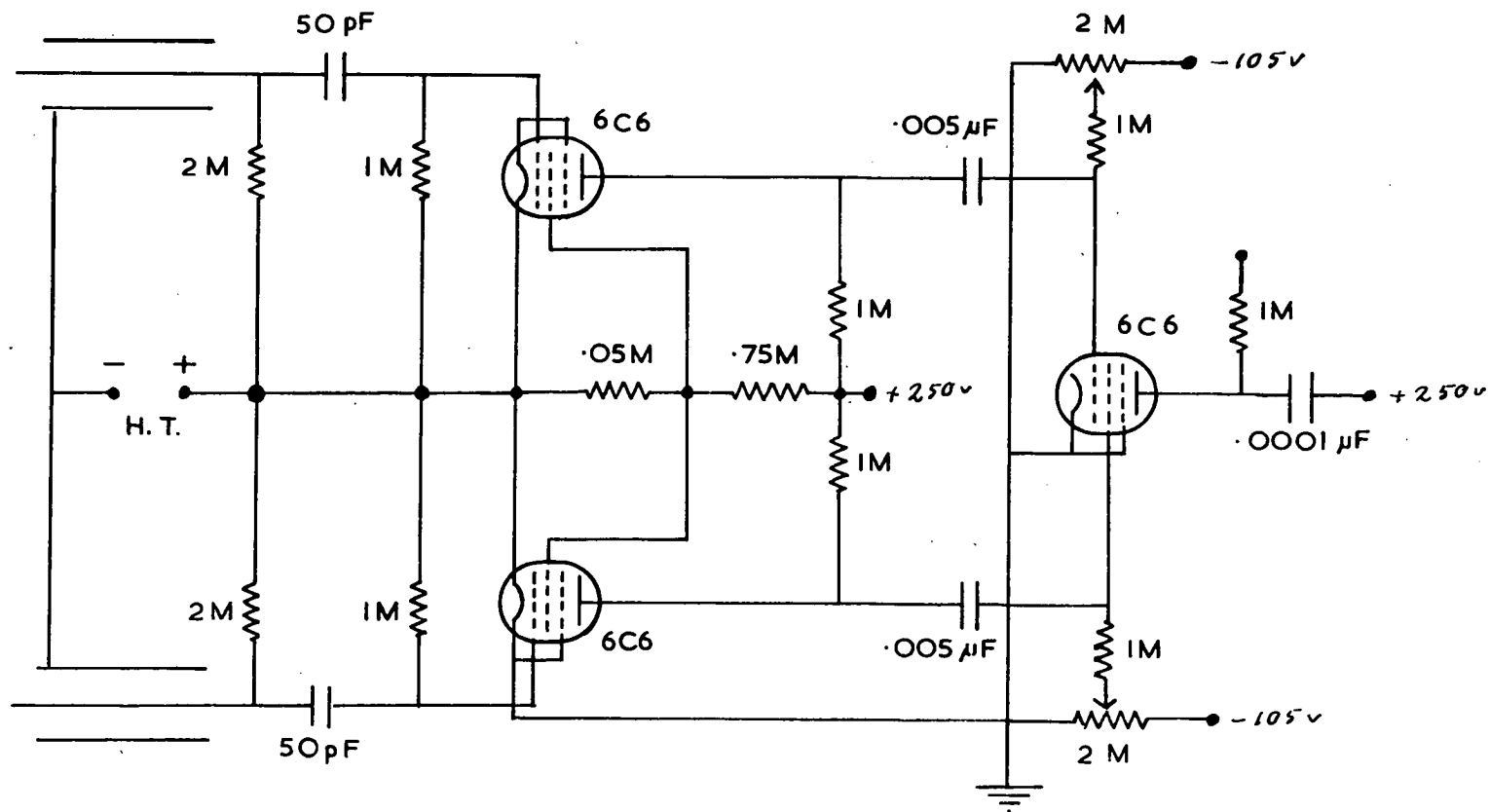
REGULATED HIGH TENSION POWER SUPPLY.

Figure 4: Regulated bias supply.



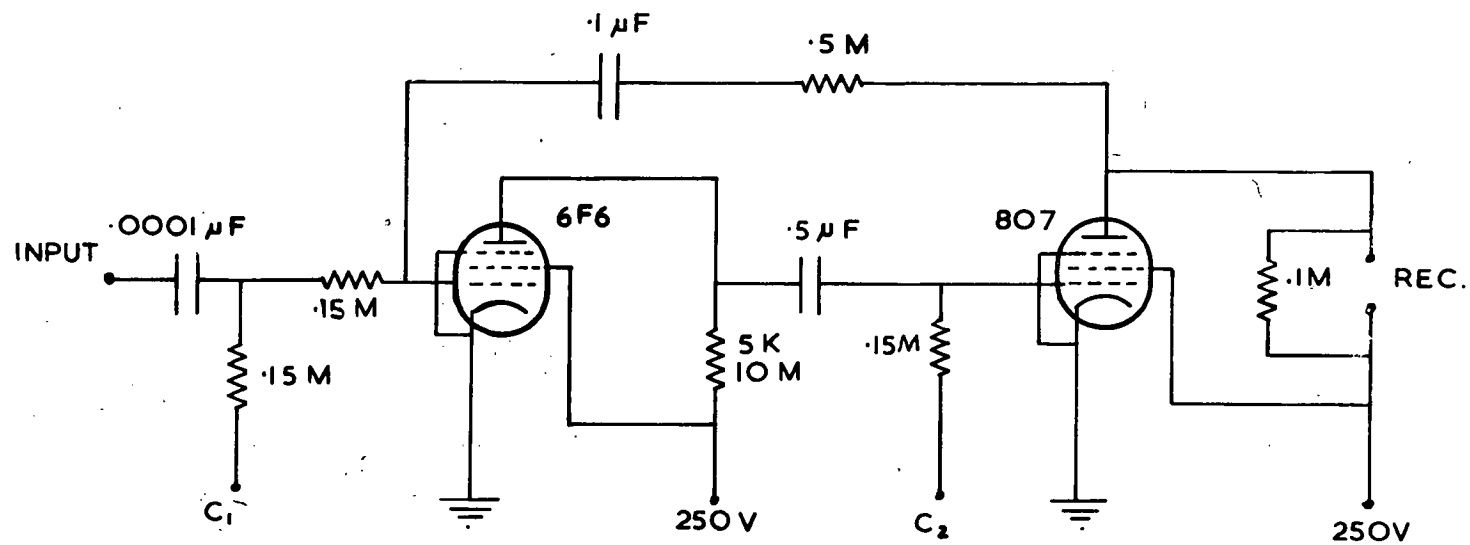
REGULATED BIAS SUPPLY.

Figure 5 - First coincidence amplifier tried with the Double Telescope Apparatus. The grids of the third tube are biased negative so that this tube conducts only when positive pulses arrive simultaneously at both grids.



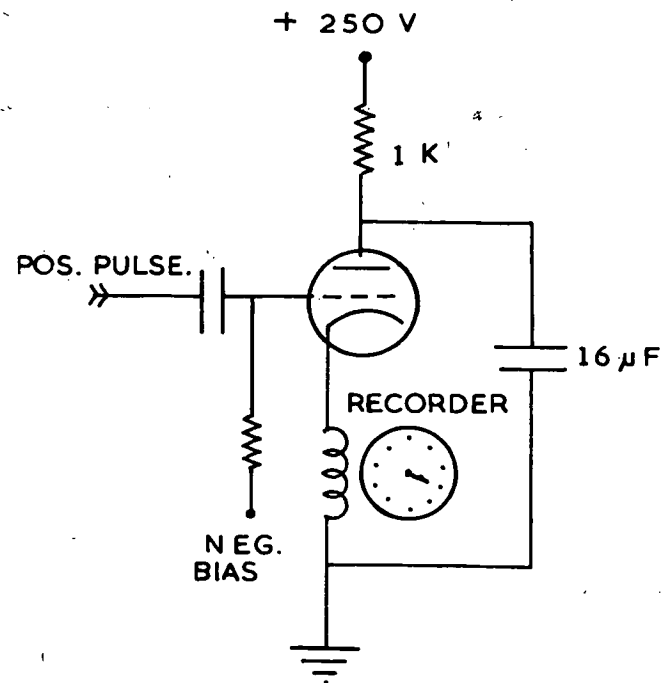
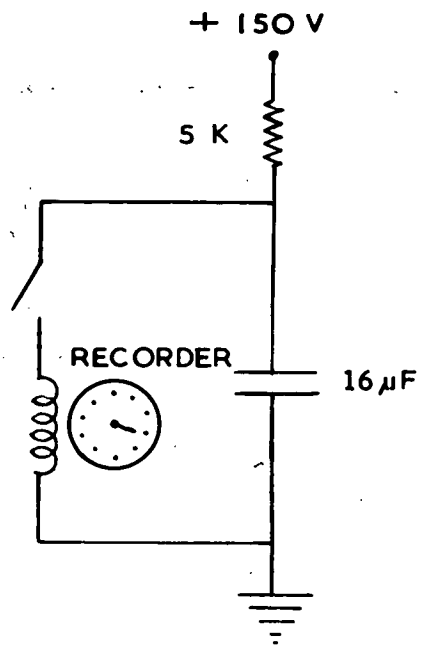
MIXER TUBE COINCIDENCE AMPLIFIER.

Figure 6 - Circuit of multivibrator tried with the
Double Telescope Apparatus. This circuit was found
unsatisfactory because it gave rise to interference.



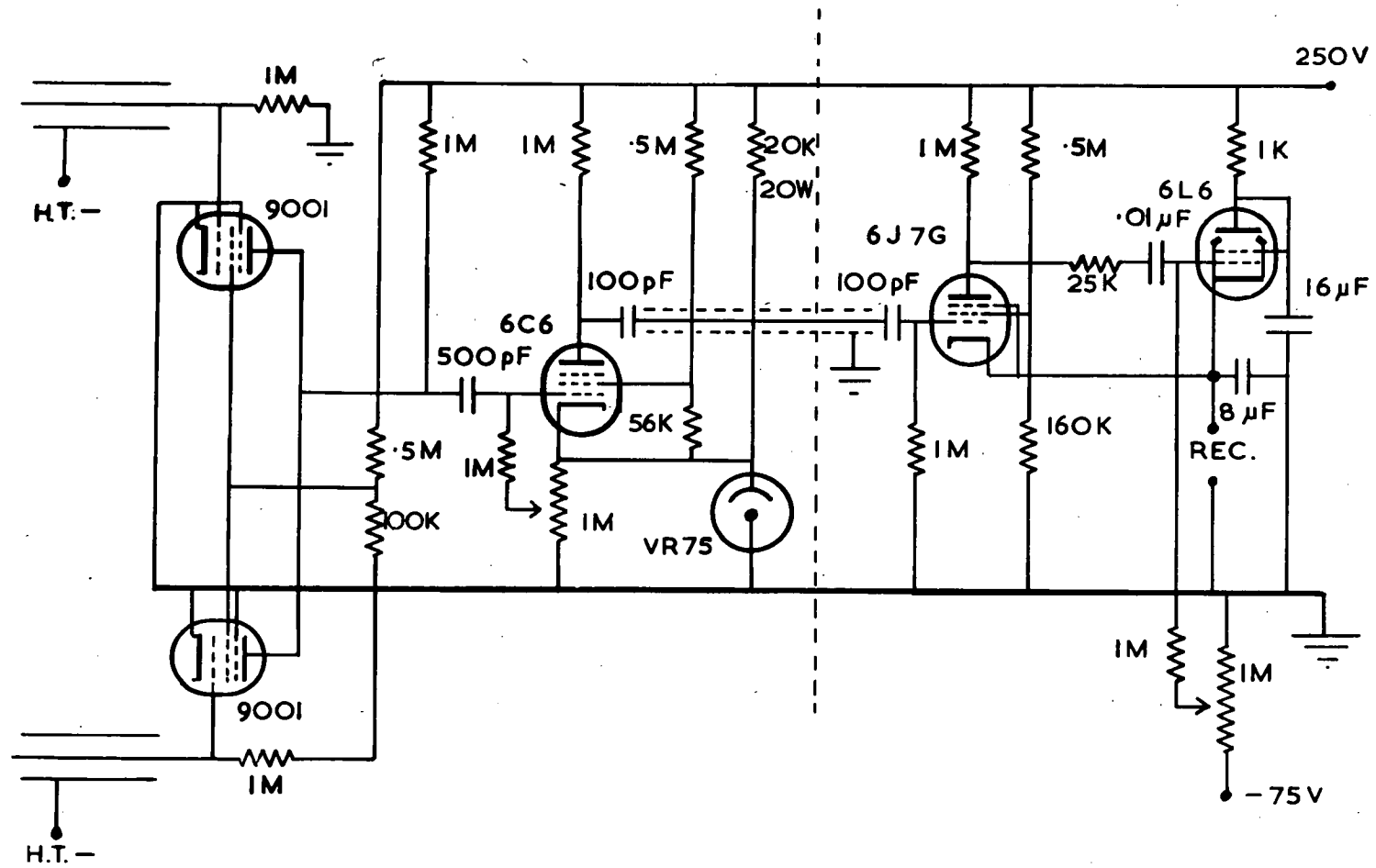
TRIGGERING MULTIVIBRATOR FOR MECHANICAL RECORDER.

Figure 7 - The left-hand circuit was used to find the power necessary to drive a mechanical register. The right-hand circuit shows how the switch can be replaced by a power tube normally biased past cutoff.



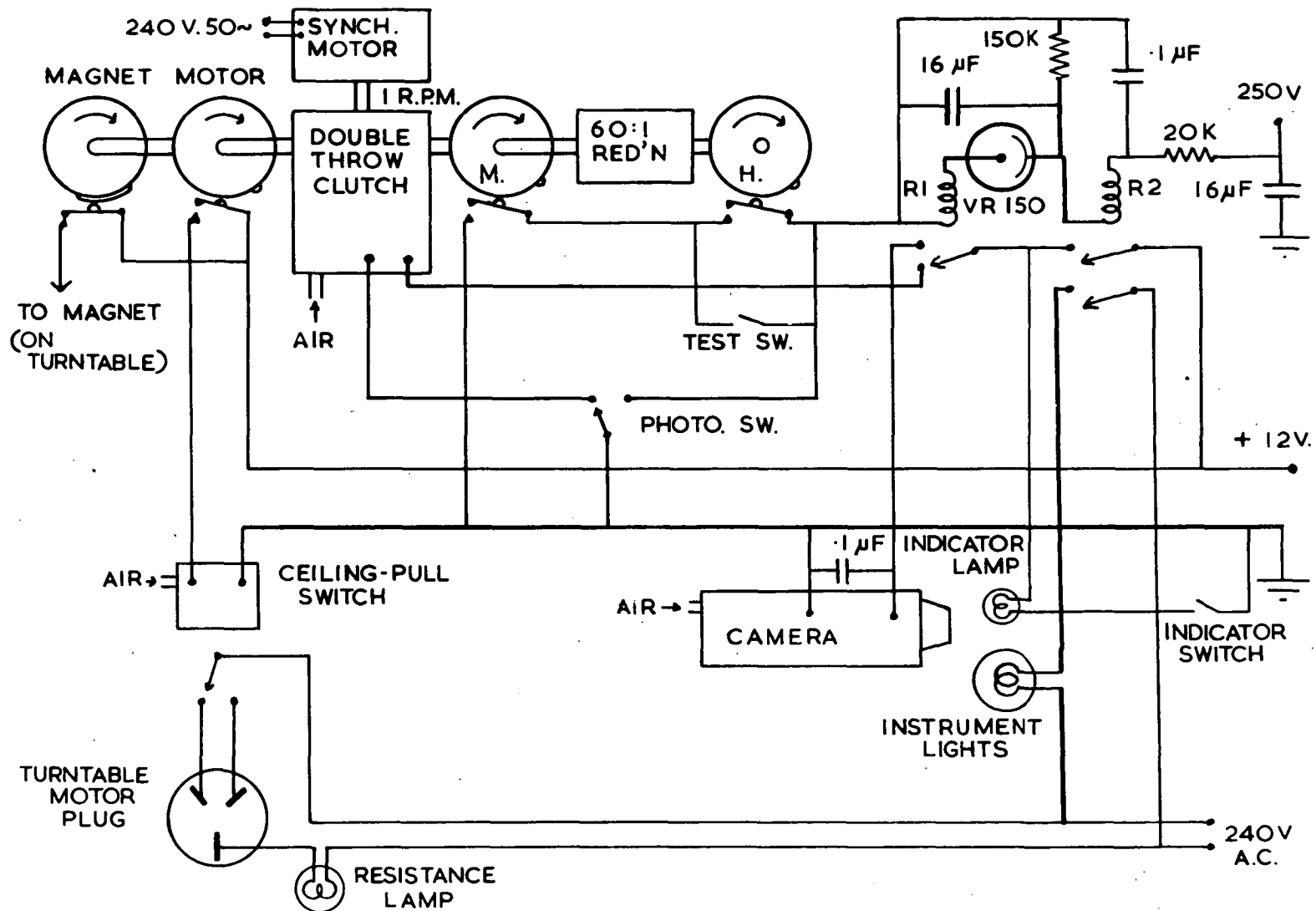
BASIC DESIGN OF CIRCUIT TO DRIVE MECHANICAL RECORDER.

Figure 8 - Coincidence amplifier and register driving
circuit used with the first Double Telescope Apparatus.



COINCIDENCE RECORDING CIRCUIT FOR ONE TELESCOPE.

Figure 9:- Timing unit and control circuit used for
controlling the apparatus and recording the results.



TIMING UNIT AND CONTROL CIRCUIT.

Figure 10 - Details of the mechanical section
of the timer.

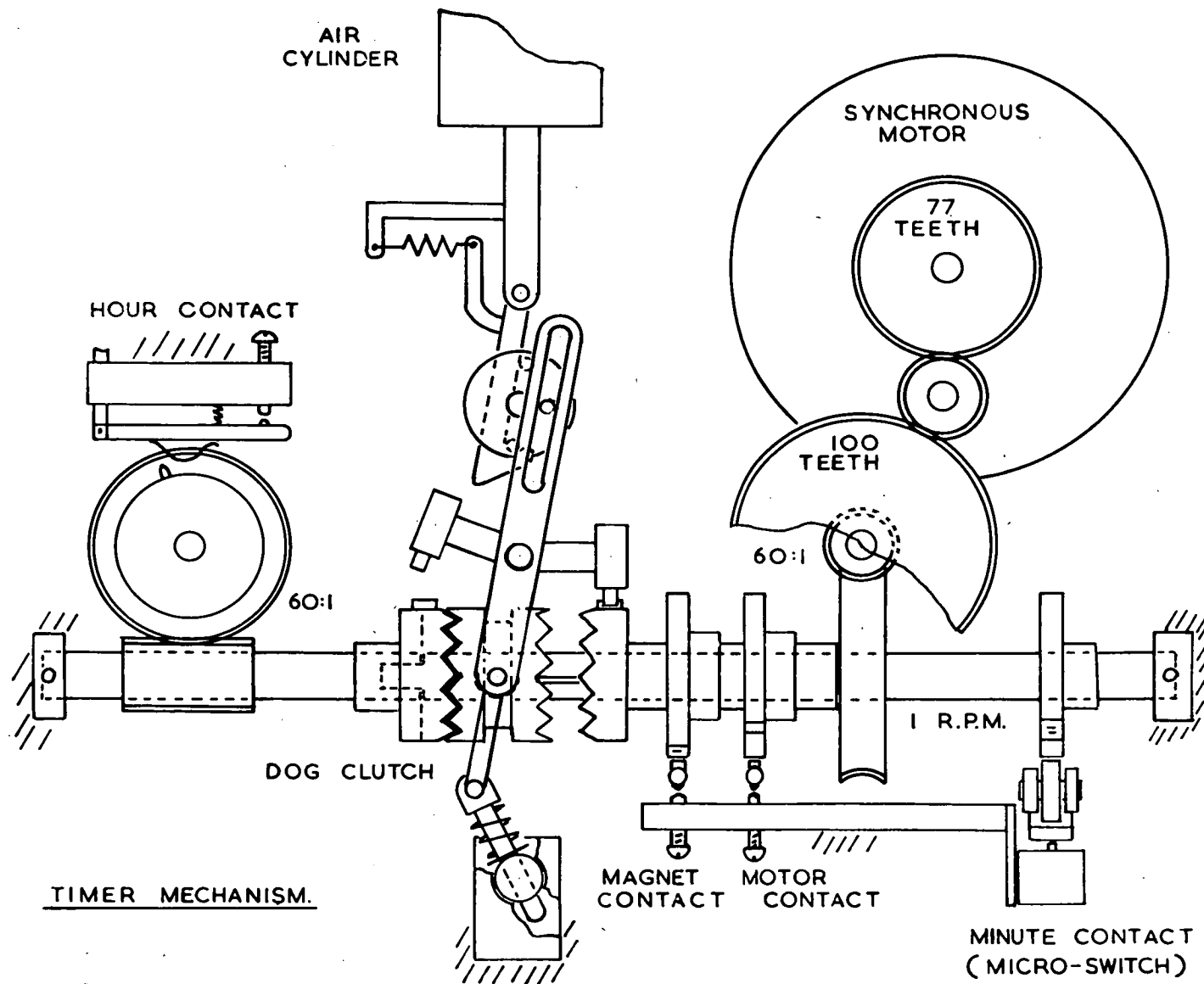
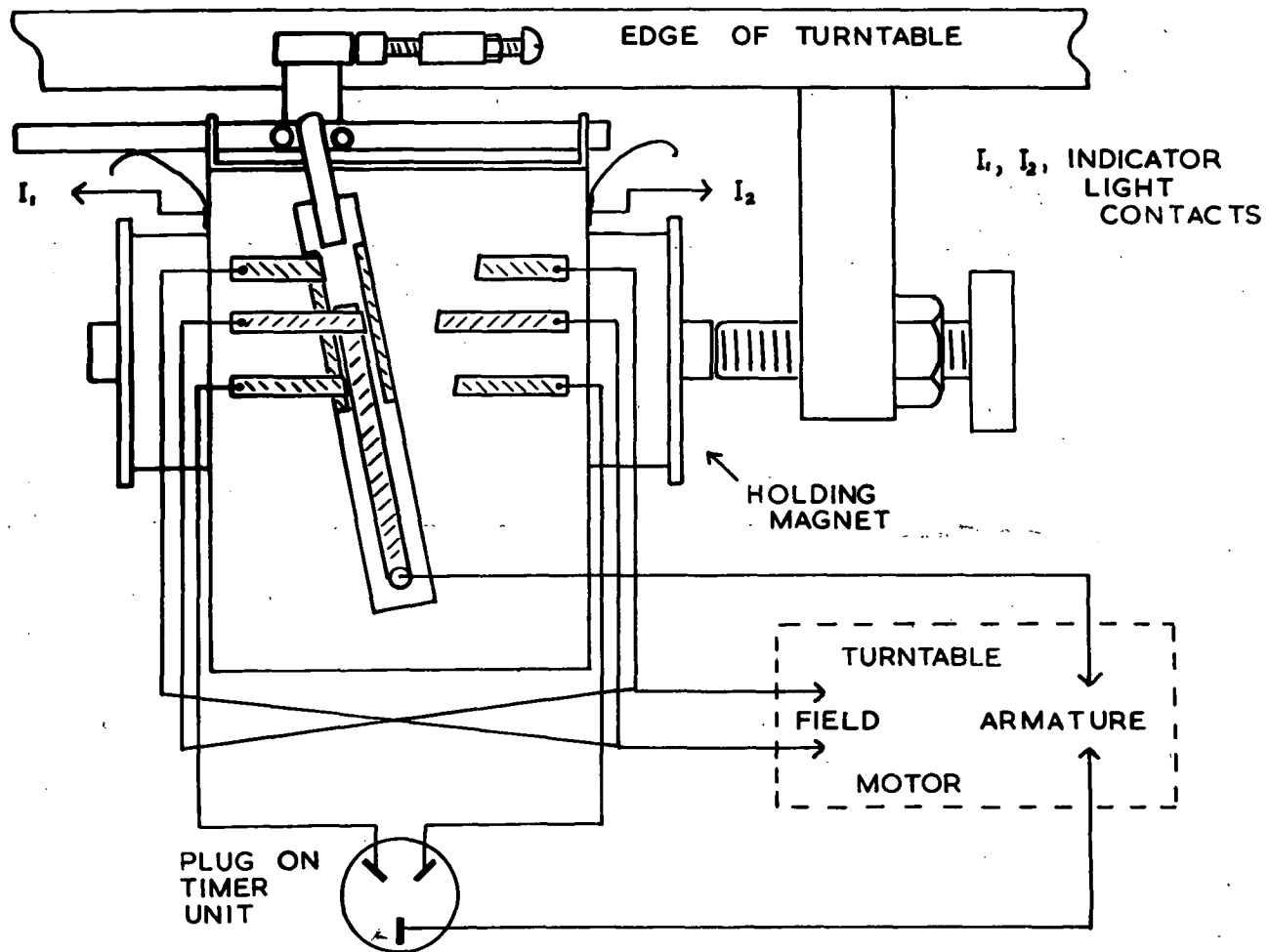
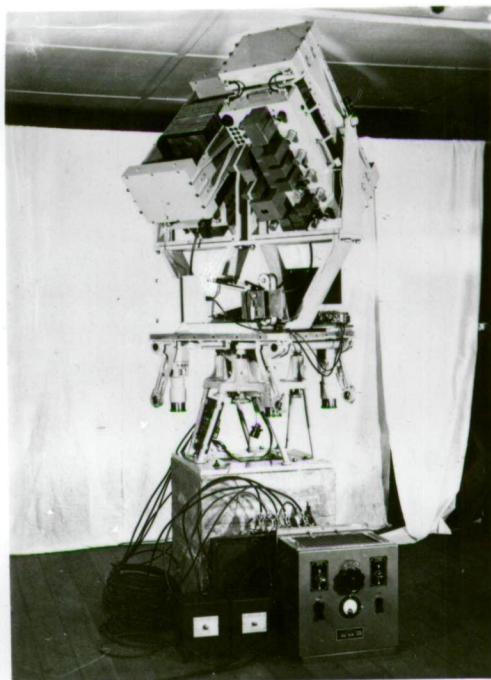
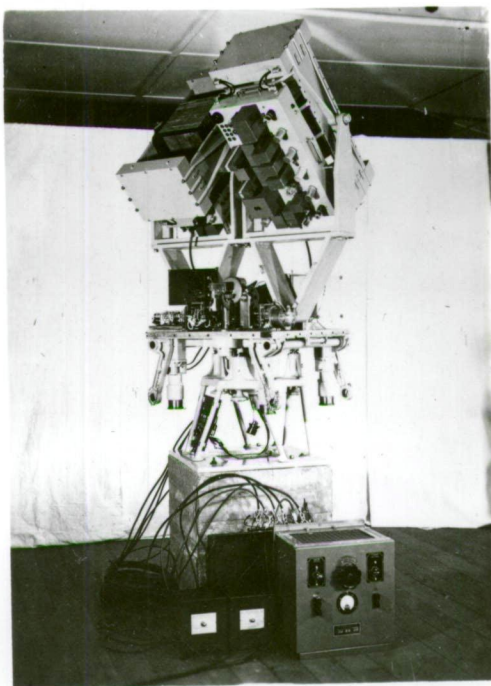


Figure 11 - Switch gear located on the turntable to
control the electric motor used to rotate the turntable.



Figures 12a and 12b - The completed Macquarie Island Apparatus at Hobart before being dismantled for packing. The turntable control gear can be seen on top of the platform in 12a, and the prototype camera mounted on the recording unit in 12b.



Figures 13a and 13b - Close-up views of the turntable drive mechanism and positioning switches on the Macquarie Island Apparatus.

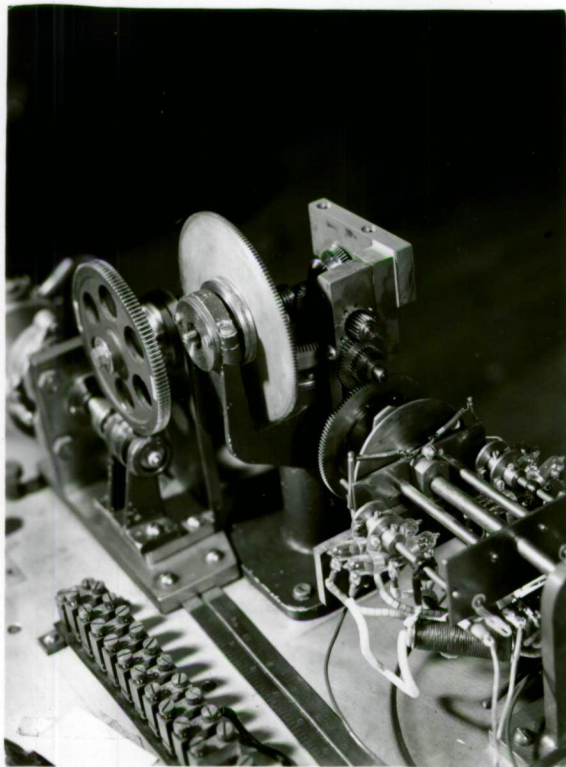
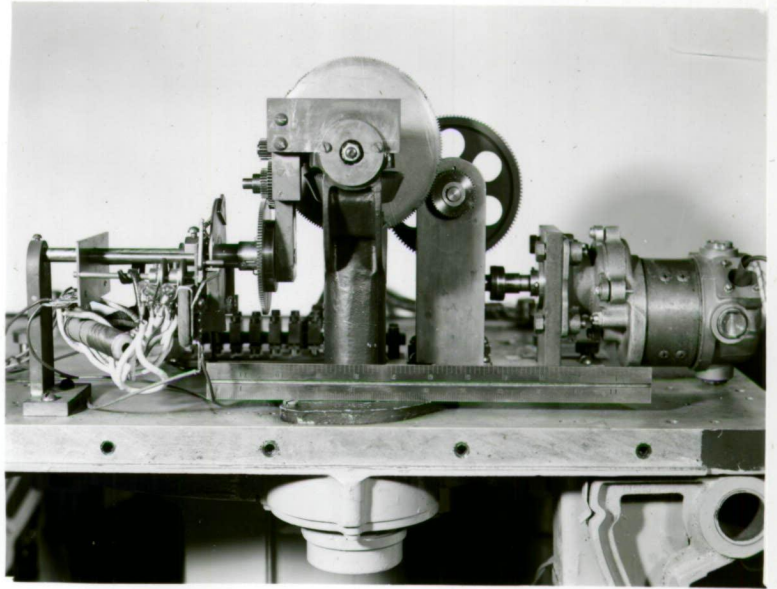
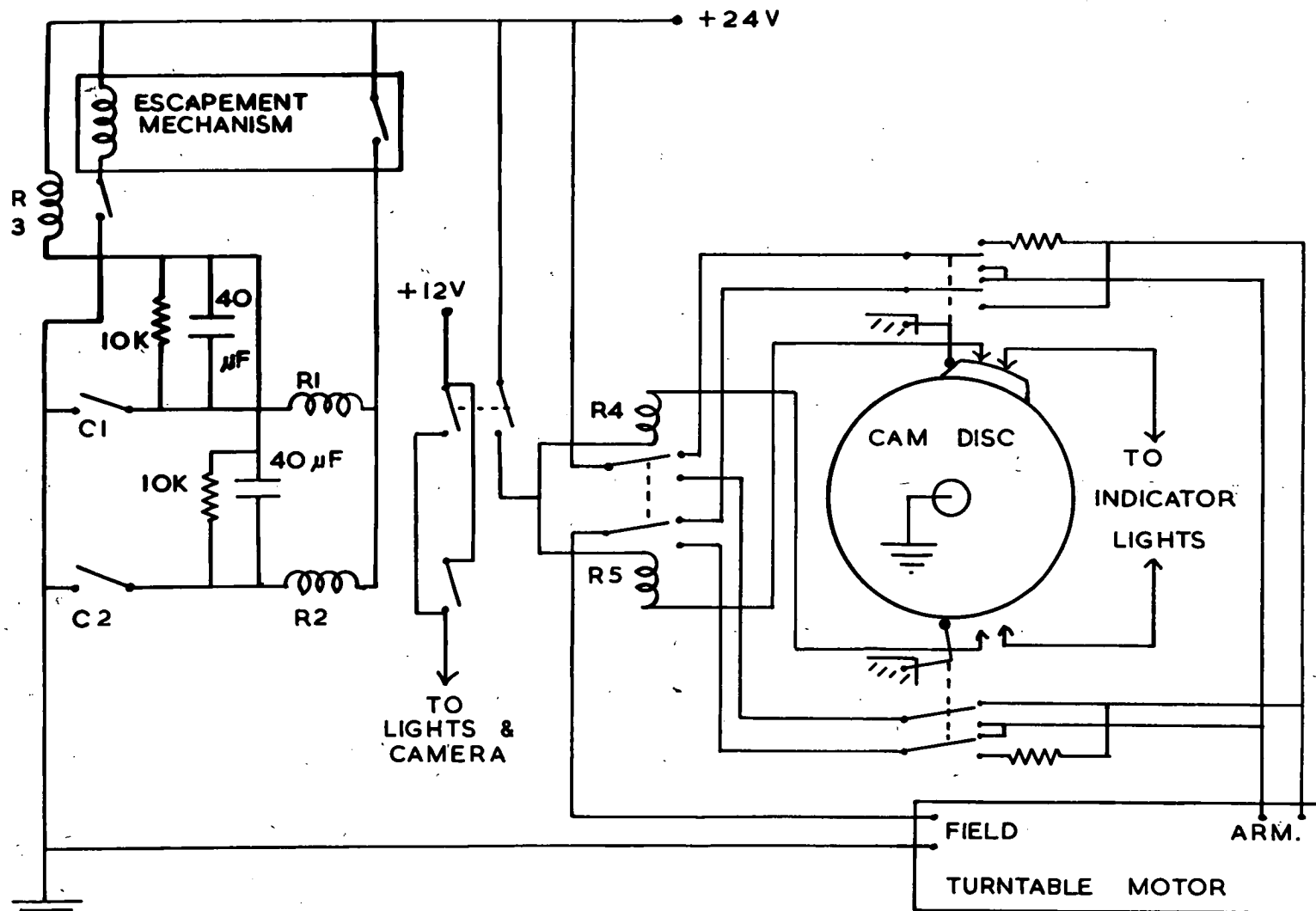


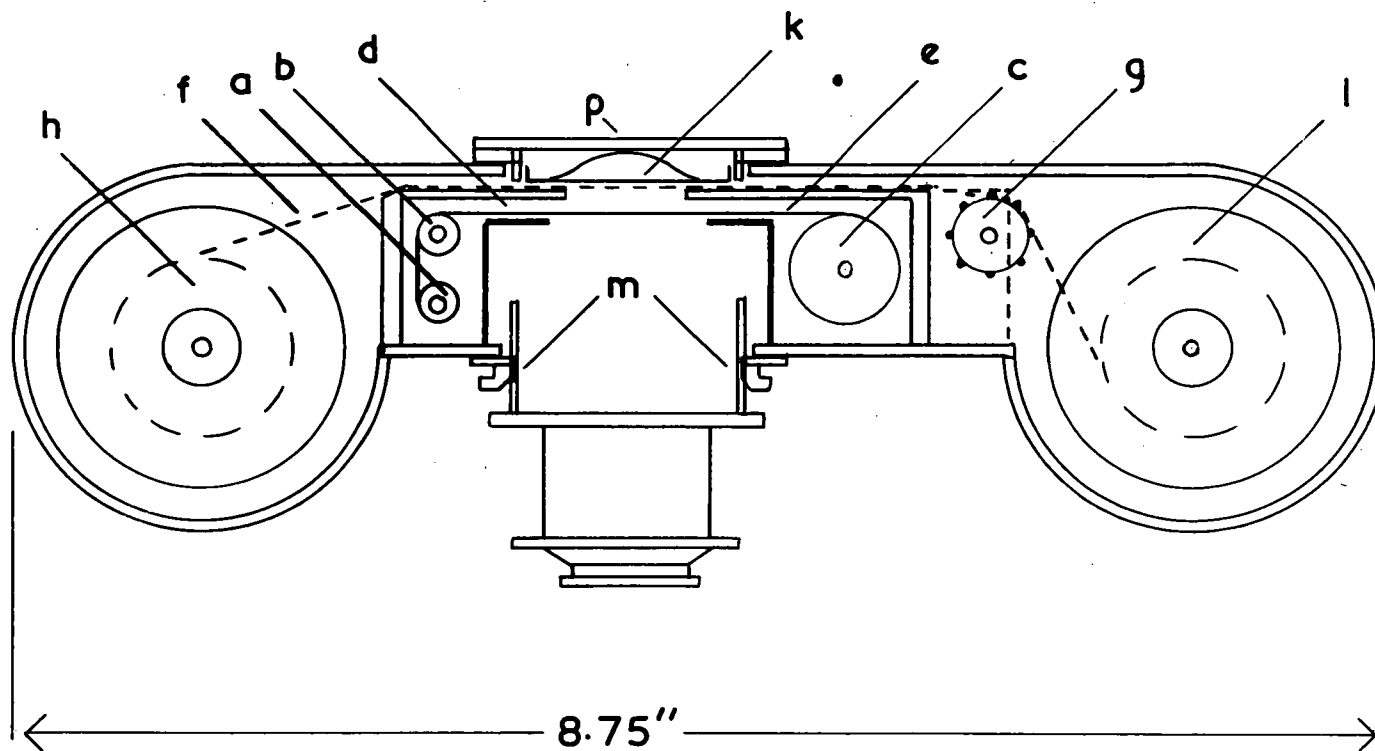
Figure 14 - Control circuit of Macquarie Island Apparatus.
The contacts C1 and C2 are located on a clock, and are closed
on the hour and one minute later.



CONTROL CIRCUIT OF MACQUARIE ISLAND APPARATUS.

Figure 15 - Positions of internal parts of 35mm. recording camera.

Key: a: trailing blind tension roller. b: leading blind tension roller. c: main roller assembly. d: leading blind. e: trailing blind. f: film. g: film transport sprocket. h: feed spool. k: pressure pad. l: takeup spool. m: Lens mount.

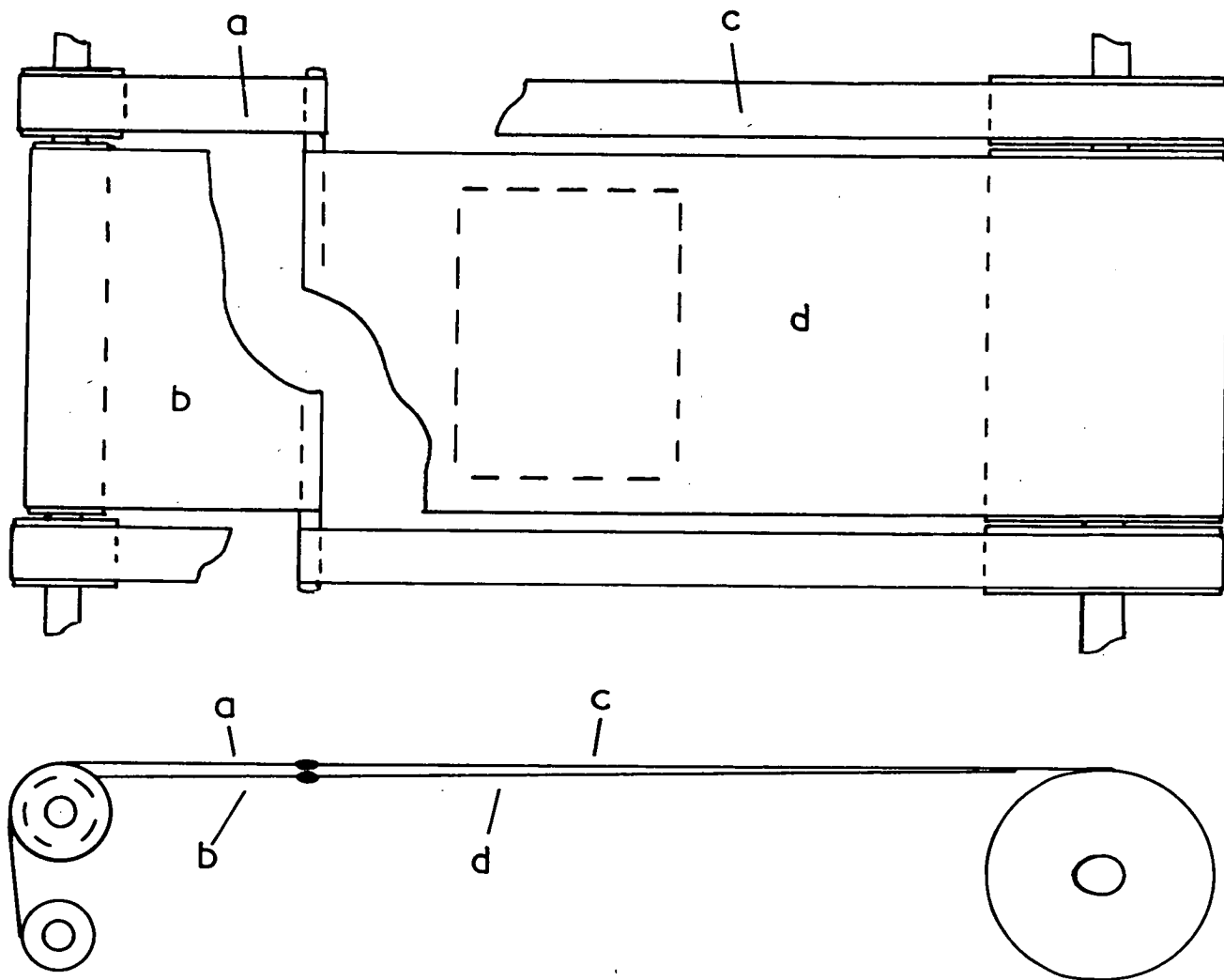


POSITIONS OF INTERNAL PARTS OF 35 MM. RECORDING CAMERA.

Figure 16 - Layout of shutter blinds in 35mm. recording camera.

Key: a: trailing blind tension tapes. b: leading blind
c: leading blind tapes. d: trailing blind.

Erratum - The positions of the letters "c" and "d" in the lower diagram should be interchanged.



LAYOUT OF SHUTTER BLINDS IN 35 MM. RECORDING CAMERA.

Figures 17a and 17b - Parts of the prototype 35mm.
recording camera which was constructed by the author.

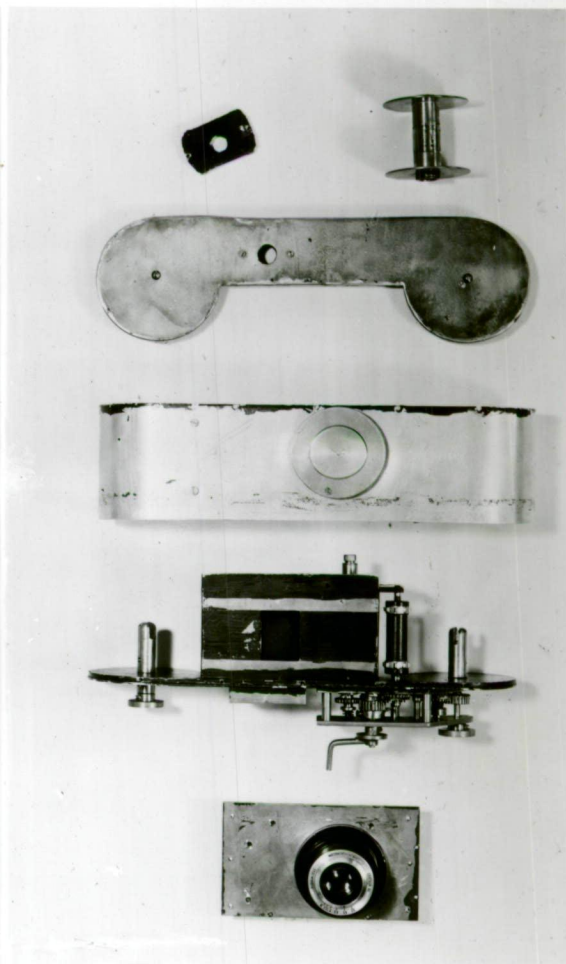
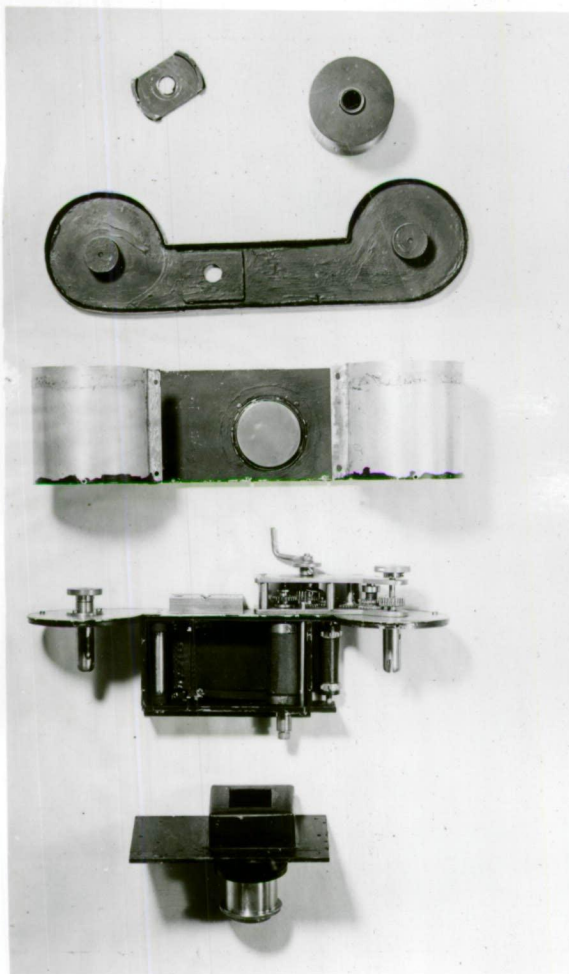


Figure 18 - Enlargement of gearbox of prototype camera.

Key: a: drive shaft. b: release disc. c: lifting flange.

d: shutter drive gear. e: sprocket gear. f: intermittent gear. g: locking plate.

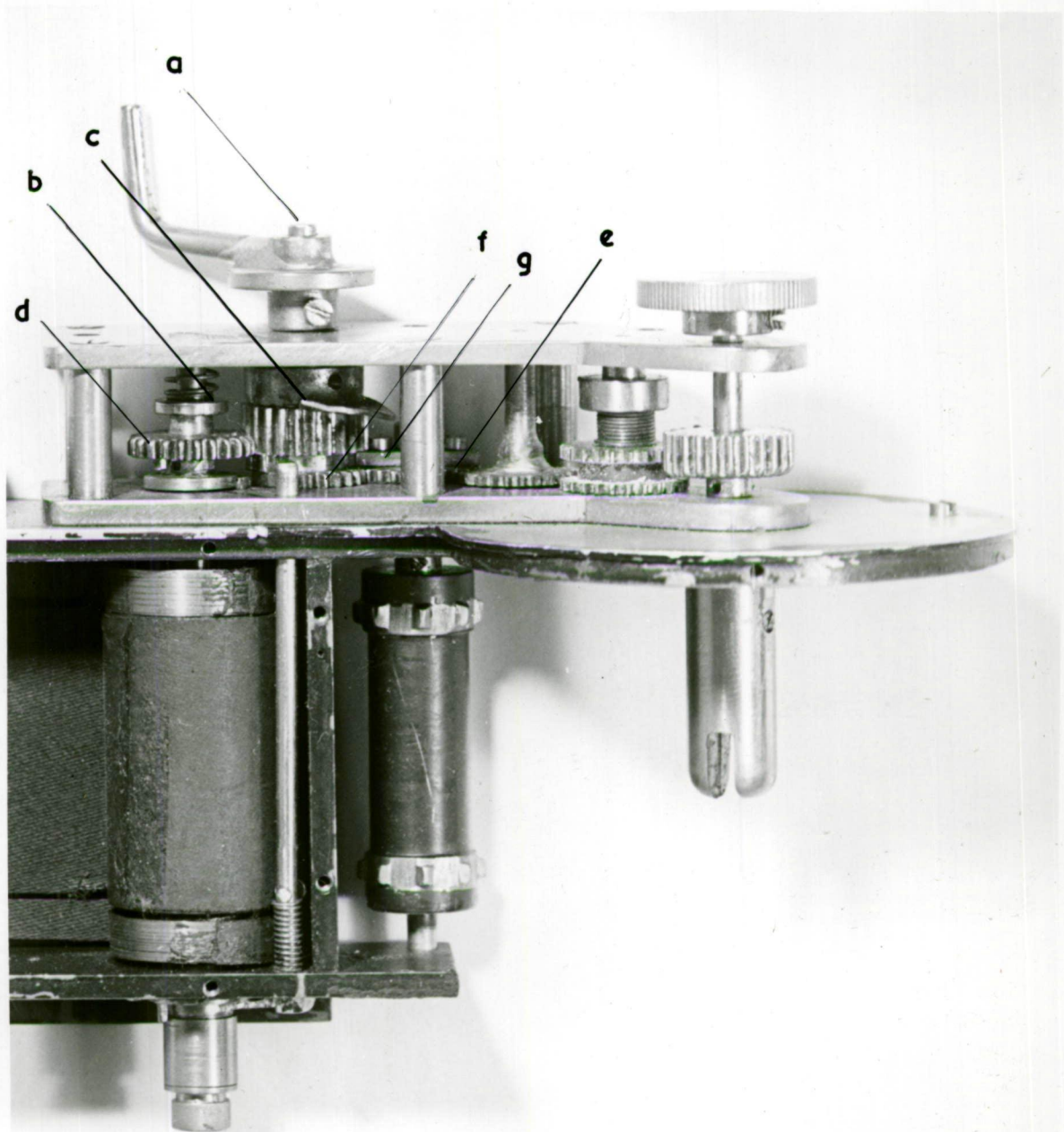
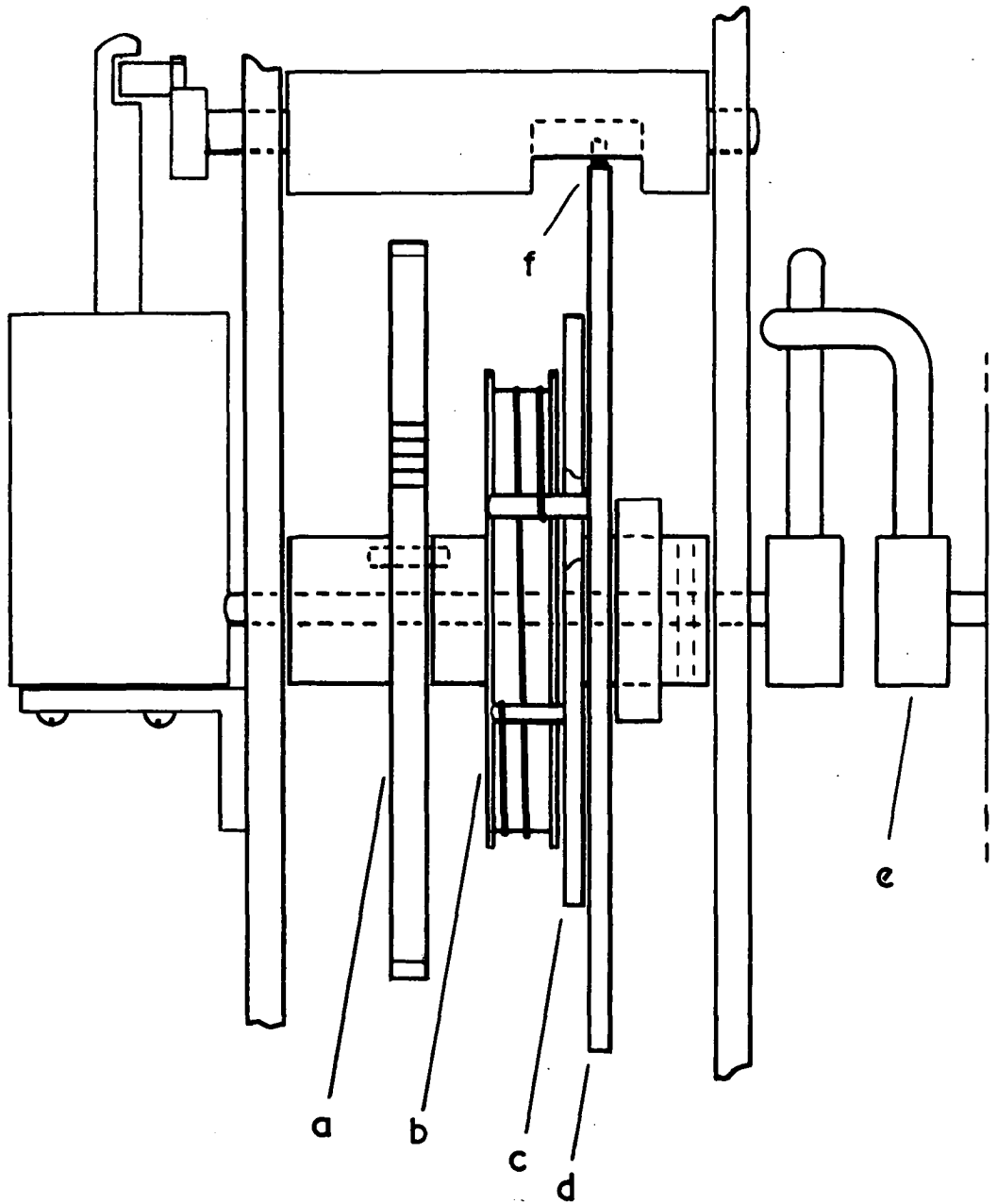


Figure 19 - First camera drive clutch used with the prototype 35mm. recording camera.

Key: a: gear driven by motor through gear train (not shown) b: drum coupled to "a". c: disc coupled to camera drive shaft. d: idling disc. e: camera coupling. f: release catch.



PROTOTYPE CAMERA DRIVE CLUTCH.

Figures 20a and 20b - Experimental camera drives
using friction clutch as described in text.

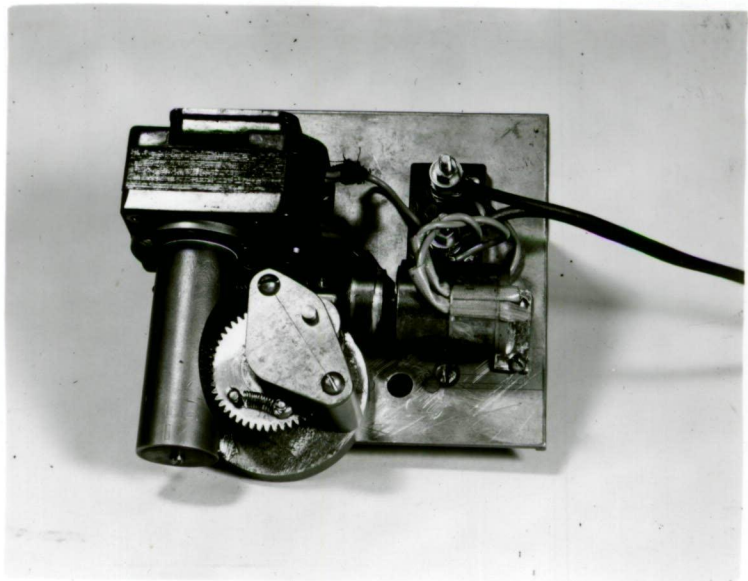
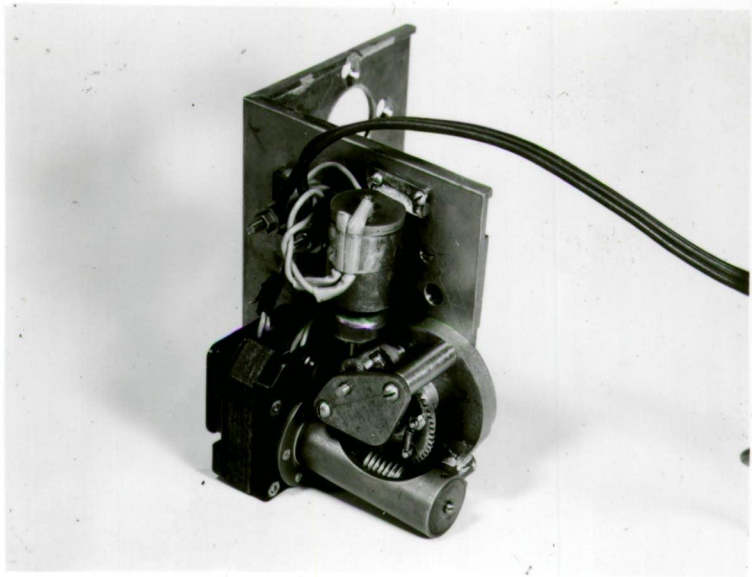
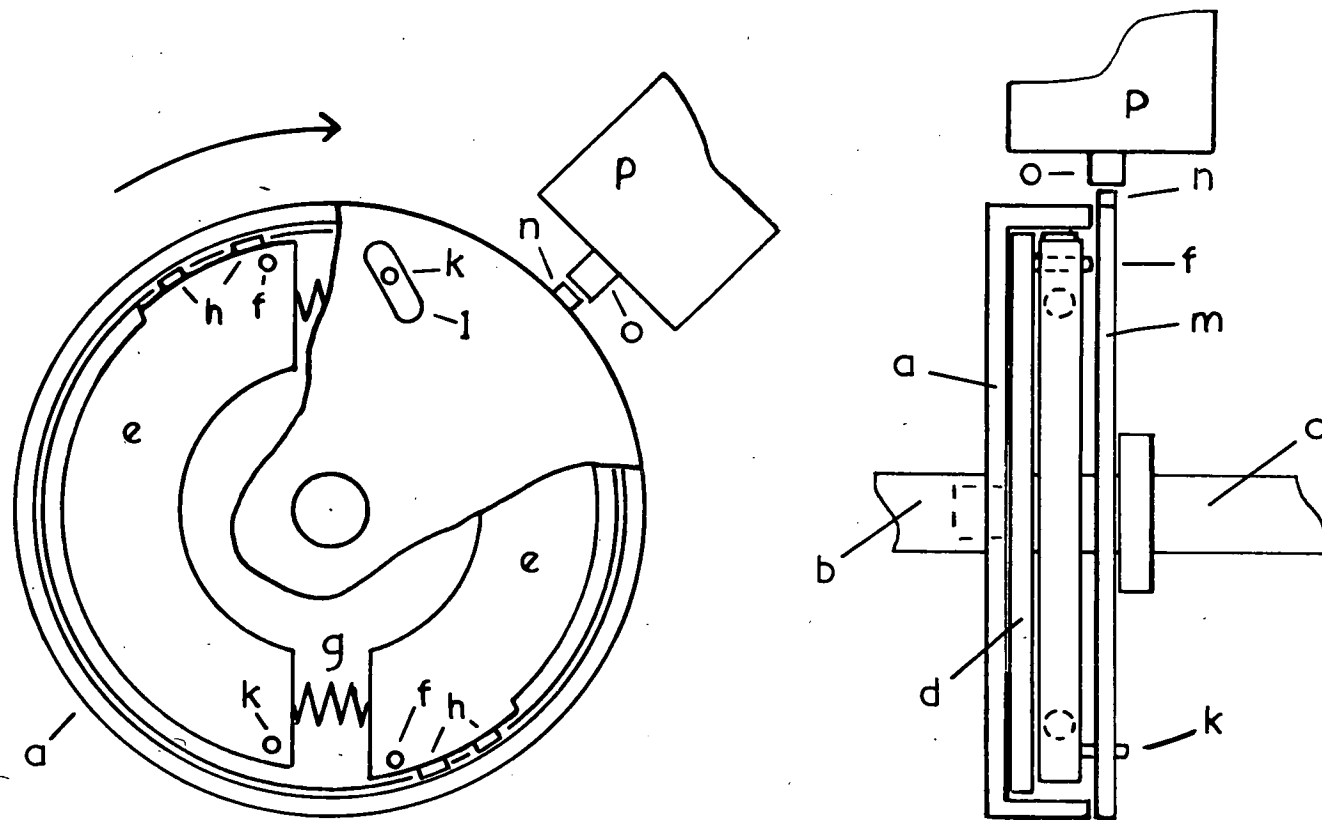


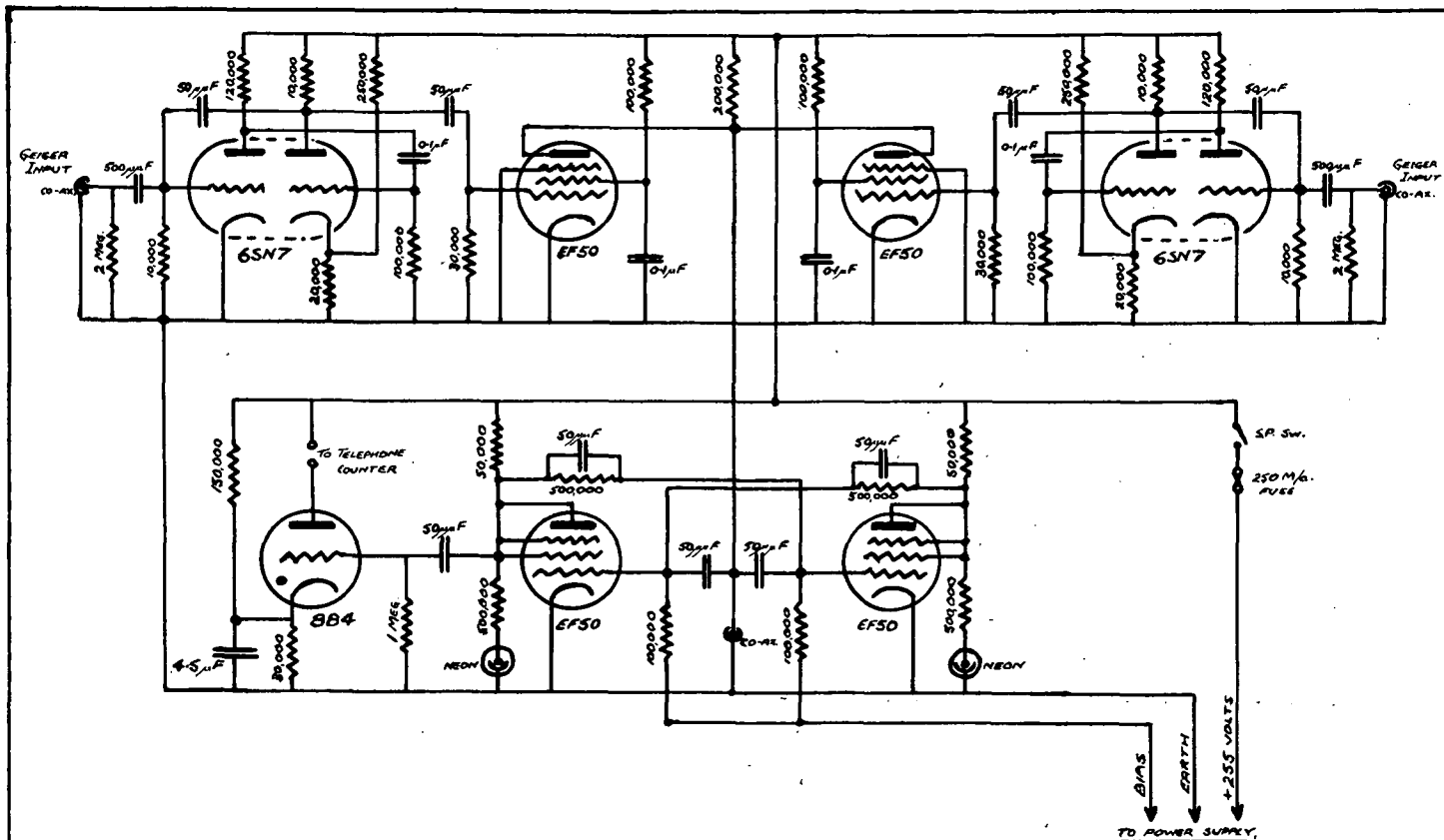
Figure 21 - Final design of camera drive clutch used

KEY: a: drum driven by motor. b: shaft from motor.
c: shaft coupled to camera. d: disc fixed to camera
drive shaft. e,e: clutch shoes. f,f: clutch shoe
pivot pins. g,g: clutch shoe springs. h,h: clutch
surfaces. k,k: clutch shoe control pins. l,l: slots
to engage pins k,k. m: clutch shoe control disc.
n: release catch. o: solenoid plunger. p: solenoid.



FINAL CAMERA DRIVE CLUTCH.

Figure 22 - Circuits designed by Mr. K.B. Fenton
for use on Macquarie Island apparatus and used on
modified Double Telescope Apparatus.



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Figure 23 - Curvature of path of meson ($1/\rho$)
against residual range in air (open scale).

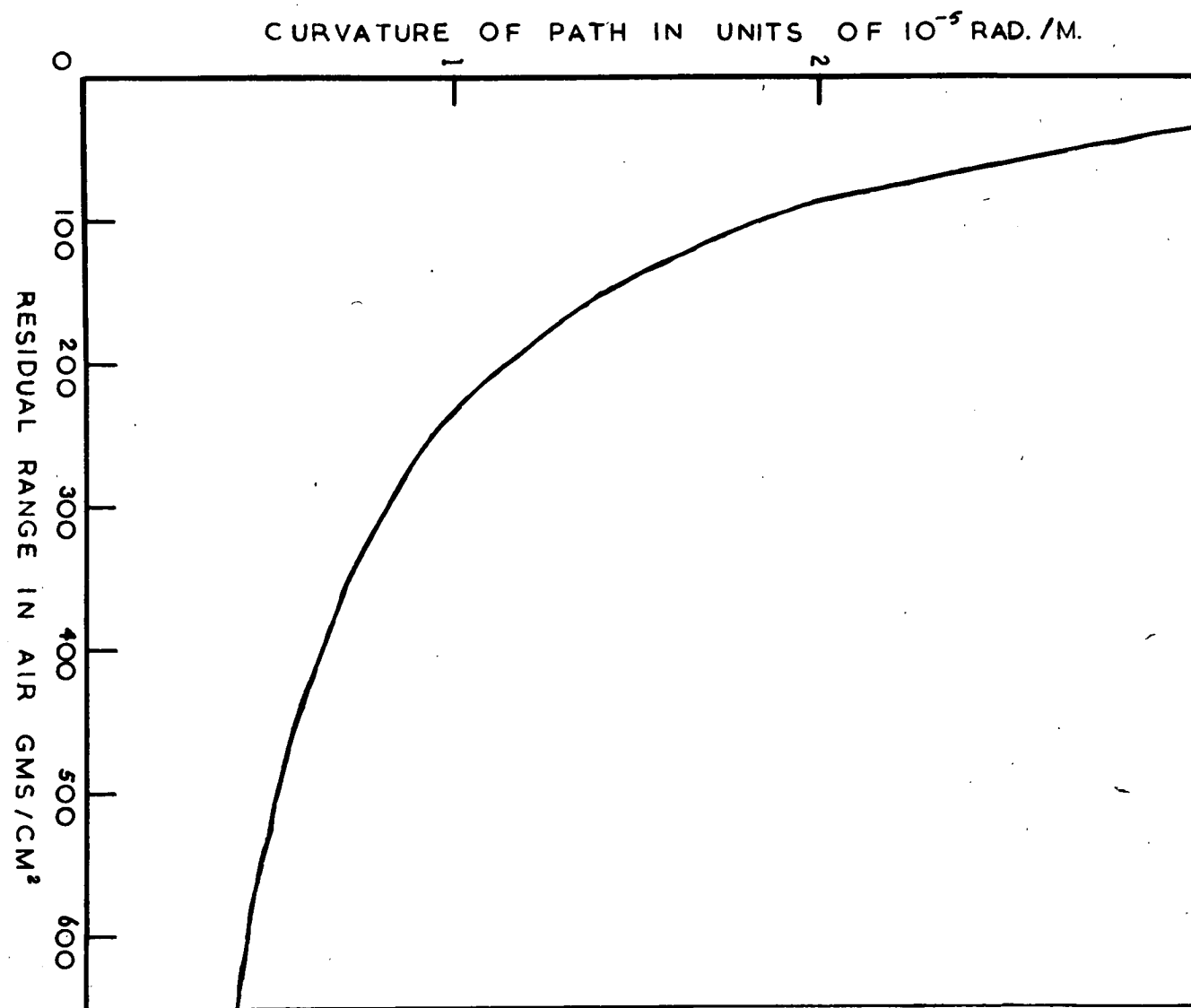


Figure 24: Curvature of path of meson ($1/\rho$) against residual range in air.

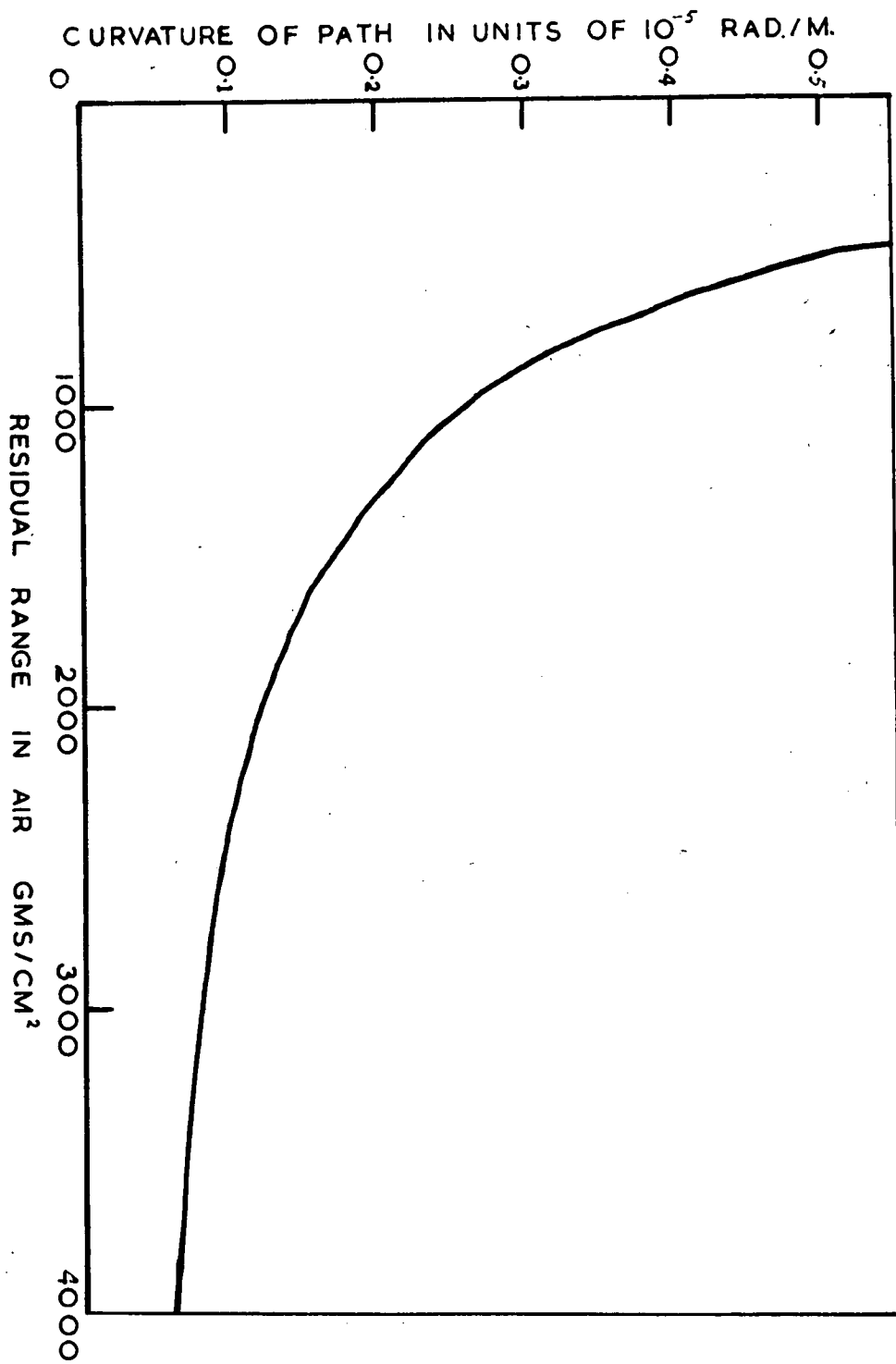
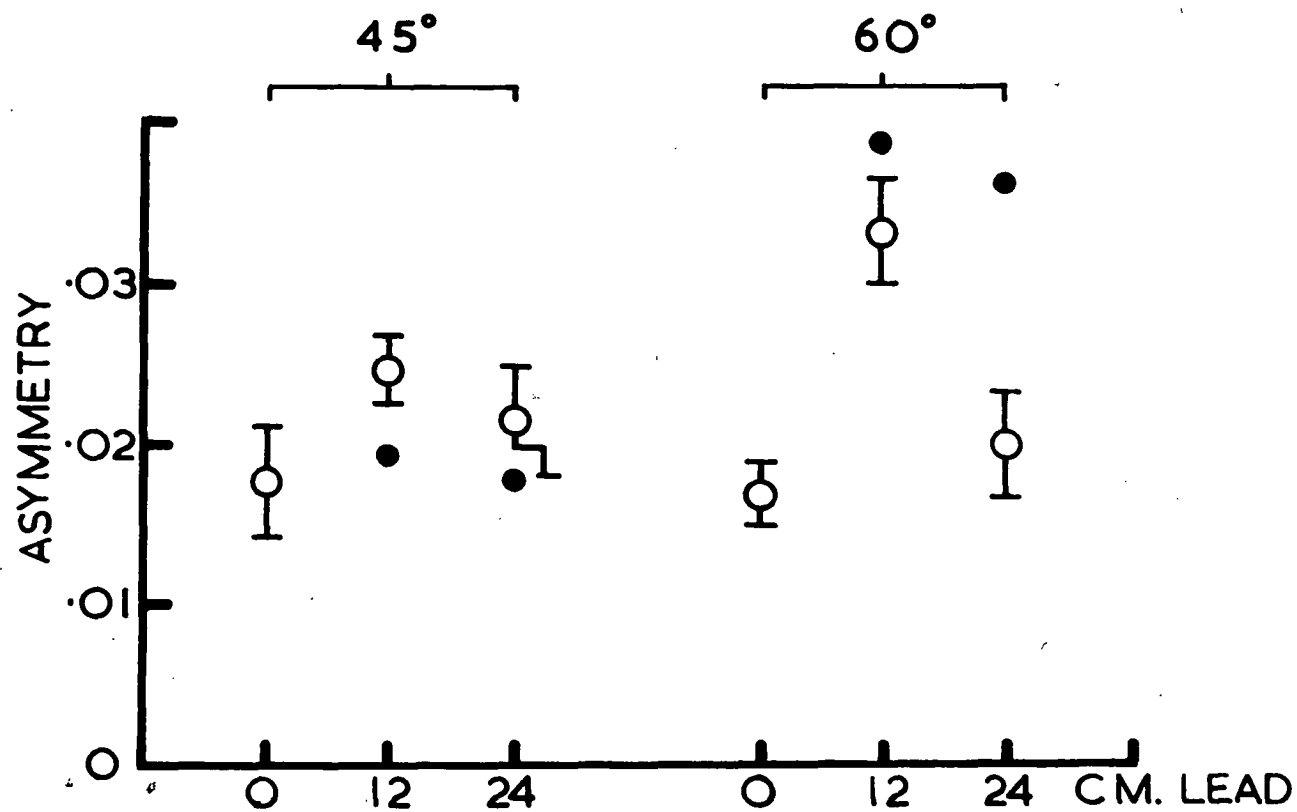


Figure 25 - The effect of lead absorber on the asymmetry at 45 and 60° zenith angles. The results are compared with the theoretical values.



○ EXPERIMENTAL RESULTS
● THEORETICAL VALUES

Figure 26 - Experimental values obtained at Hobart
using 12 centimetres of lead absorber in the telescopes.
The curve shows the corresponding theoretical values
calculated as described in the text.

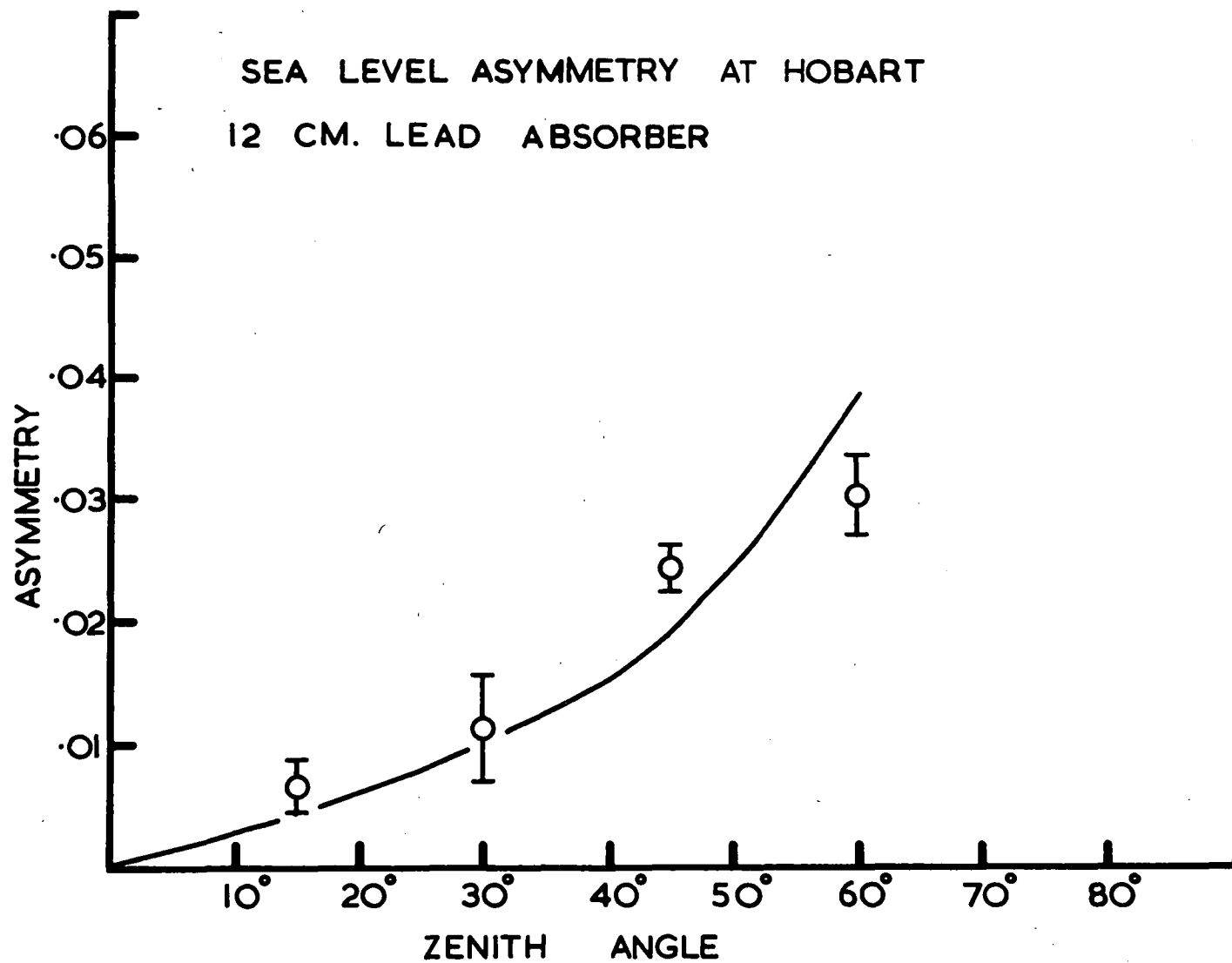


Figure 27: Experimental values obtained at Macquarie Island using 12 centimetres of lead absorber in the apparatus. The curve shows the theoretical values obtained by reducing the theoretical values for Hobart in the ratio of the horizontal component of the magnetic field.

SEA LEVEL ASYMMETRY AT MACQUARIE ISLAND

12 CM. LEAD ABSORBER

