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The Latitude Effect for Cosmic-Ray Showers

H. V. NEHER AND W. H. PICKERING
California Institute of Technology, Pasadena, California

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Cosmic-ray observations have been taken with Geiger counters on a voyage from San Francisco to Colombo via Japan and return via Australia. The apparatus used possesses some interesting features and is described at length. The latitude effect for vertical coincidences is found to be 14.5 percent in the region of the Dutch East Indies and 10 percent in the Pacific Ocean. The showers show a much smaller variation with latitude, only about 6 percent being found in the region of the East Indies. This result is interpreted as meaning that the latitude sensitive part of the radiation is not as efficient at producing showers as the nonlatitude sensitive radiation. Qualitatively at least, such behavior is consistent with the hypothesis that the latitude sensitive radiation is due to incoming electrons.

EXPERIMENTS indicating the existence of a small latitude effect for the cosmic-ray showers measured by three Geiger counters placed out of line beneath a thin plate of lead, have been reported by Johnson and Read,[1] and Pickering.[2] In both these cases, however, instrumental and statistical difficulties have precluded the possibility of very accurate results. Last year it was felt that the development of the Neher-Harper circuit[3] which permits the use of very large counters, was the answer to the experimental difficulties of the problem, and accordingly this investigation was undertaken. During the course of the experiment the counters were taken from San Francisco to Colombo via Japan, then from Singapore to Melbourne and from Auckland to Vancouver. Measurements were made of the variation of both the vertical rays and the showers.

[1] Johnson and Read, Phys. Rev. **51**, 557 (1937).
[2] Pickering, Phys. Rev. **49**, 945 (1936).
[3] Neher and Harper, Phys. Rev. **49**, 940 (1926).

APPARATUS

The counters used in this work were made of hard drawn copper tubing $3\frac{1}{2}$ in. in outside diameter and with a wall thickness of $\frac{1}{16}$ in. The active length of the counters was about 14 in. Since glass tubing of the size necessary to enclose these counters would be both fragile and expensive, a somewhat unusual type of construction was employed (see Fig. 1). This design was very satisfactory in actual service. Only one counter out of twelve was broken by rough handling, and none of the remainder developed any leaks.

The gas used for filling the counters was a mixture of 80 percent argon and 20 percent dry air. A pressure of about 5 cm made the threshold voltage about 1450 volts, and all the counters were filled until they had the same threshold. After about a year, these counters operate with practically their original characteristics.

The Neher-Harper circuit possesses at least one very marked advantage over the conventional circuit when used under conditions such

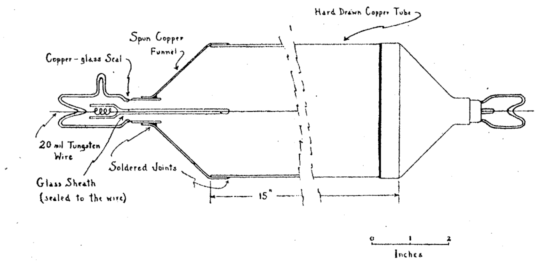

FIG. 1. Design of counters.

as those experienced on a long sea voyage. In this circuit the highest resistance which has to be maintained fairly constant is 15 megohms as compared to the conventional circuit with its resistances of about 10^9 ohms. Of course, in both circuits leakage between elements of the counter has to be avoided, but again in the new circuit the requirements are not so exacting. As an example of the practical advantage of this matter, during this voyage the only time that humidity gave any trouble was once when the rain was actually beating on the apparatus.

With this circuit only one stage of amplification is necessary to give a pulse in the right direction to be fed to the mixing tube in the usual way. In our case the mixing tube was an 885 type thyratron which operated a mechanical counter through the circuit of Fig. 2. This circuit has the advantage that a fast relay is used directly in the plate circuit of the tube, and the contacts on this relay make, but do not break, the comparatively large current which operates the mechanical counter.

The chief problem in operating Geiger counters on ship board is that of the power supply for the counters. Practically all ships generate direct current at a voltage that is liable to fluctuate widely. In our case a d.c. to a.c. converter operating on about 65 volts had power supplied to it through a motor driven rheostat. The terminal voltage at the converter was balanced against $67\frac{1}{2}$ volts of dry cells. Through a relay system any unbalance was corrected by the motor driven rheostat. Since the a.c. output of the converter was at a constant load, the output voltage remained quite constant except perhaps for short period fluctuations. The high potential on the counters remained constant to about 10 volts.

Two complete triple coincidence sets were taken, and accordingly care had to be taken to prevent pickup between the sets. Complete shielding was necessary, but a filter circuit in the high tension supply to each set was later found to be unnecessary. Each counter together with its extinguishing tube was placed in a cage of brass screen, then connected to the amplifier and recorder by shielded cable. Both sets, together with the auxiliary equipment were operated in a small tent that could be set up on the top deck of the ship.

Experimental Procedure

In order to measure the vertical intensity of the radiation the counters were arranged in a vertical plane with their axes horizontal and with a distance of 10 in. between the top and bottom counters. This means that the extreme limits of the solid angle from which rays could be counted were about $41\times 111°$. However, because of the variation in sensitivity of a counter train most of the counts come from the region near the axis of the train, and in this case, with isotropic radiation, half the counts would be due to rays included in an angle of $20\times 55°$. In the actual case the angle will be somewhat further restricted. The counters were not suspended from gimbals; however, as good weather was experienced on all but two days of the voyage, the error hereby introduced is felt to be negligibly small. That this is indeed the case is shown by the fact that readings taken with the ship in port do not differ noticeably from the corresponding readings at sea.

The showers were measured with the counters arranged as shown in Fig. 3. The lead plate above the counters was 1.6 cm thick and of an area sufficient to cover the two lower counters. With this arrangement it is clear that the rolling of the ship would exert even less effect than with the counters vertical.

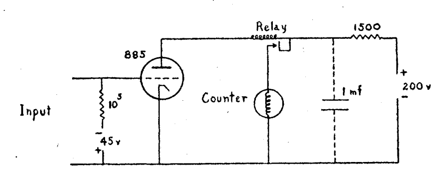

FIG. 2. Circuit to operate mechanical counter.

Vertical coincidences were observed at the rate of about 45 per minute, and showers at about 3.7 per minute, so that in a 24 hour run about 60,000 vertical coincidences and 5000 showers were obtained. Once in each 24 hours the two sets would be interchanged so that each measured both showers and vertical rays. In this way a check was obtained on any change in sensitivity. A record was made of the ship's position, the barometer, the temperature and the humidity. There is no apparent corelation between the results and either the temperature or the humidity. Barometer corrections were applied as given by Stevenson and Johnson.[4] Remarkably little change in the barometer occurred during the trip except for one storm, and hence the actual amount of the barometer correction is not critical. During the storm the corrected reading is too low, but this is probably due to the rolling of the ship and not to the use of the wrong correction.

Experimental Results

Statistically it is to be expected that a probable error of less than $\frac{1}{2}$ percent would be obtained in each day's vertical run, and about 1 percent in each day's shower run. Experimentally the consistency is not quite this good but nevertheless it is very satisfactory. Another encouraging feature of the results is the fact that the readings taken at Honolulu on the return voyage are consistent with those taken at the same place on the outward voyage almost six months previously. The two sets did not give identical readings, one being about 3 percent higher than the other for both showers and vertical coincidences. The reason for this is presumably a difference in the efficiency of some of the counters. Since this difference seemed to remain constant throughout the experiments it is a simple matter to correct for it. A check was made on the rate at which accidental coincidences were scored, and it was found that with the three counters in a horizontal plane and separated by several feet, both sets recorded about 0.06 counts per minute. As this is only about 0.13 percent of the counting rate for vertical coincidences, and about 1.6 percent of the counting rate for

[4] Stevenson and Johnson, Phys. Rev. **47**, 578 (1935).

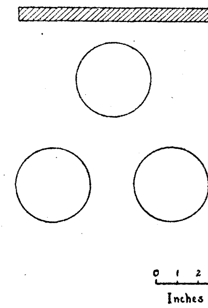

Fig. 3. Arrangement of counters to detect showers.

showers, it is clear that the accidental coincidences may be safely neglected.

The results for the vertical coincidences are plotted in Fig. 4, the ordinates being geomagnetic latitude. An examination of the curve shows very clearly that there is a latitude effect for the coincidences measured in this way, of about 14.5 percent in the region of the Dutch East Indies, and about 9.5 percent in the Pacific Ocean. In Fig. 5 the results for the showers have been similarly plotted. Only the data for the voyage from San Francisco to Colombo are shown in this curve as the remaining data show too much scattering of the points to enable a satisfactory curve to be drawn. Fig. 5, however, indicates that the latitude effect for the showers in the region of the East Indies amounts to about 6 percent. There is also some indication that the "shelf" extends to a lower latitude than in the case of the vertical radiation.

Discussion of Results

The curves of Fig. 4 show clearly the existence of both the latitude and longitude effects for the vertical rays. The two curves follow quite closely those obtained with electroscopes in the same regions.[5] This result is not in agreement with previous observers who all obtain latitude effects for the vertical rays somewhat larger than those reported with electroscopes.[1, 2, 6] Since the only apparent difference in the experimental conditions in this case is that a somewhat larger solid angle is subtended by the counters, it may be that this will account for the different

[5] Millikan and Neher, Phys. Rev. **47**, 205 (1935).
[6] Auger and LePrince Ringuet, J. de phys. et rad. **5**, 193 (1934).

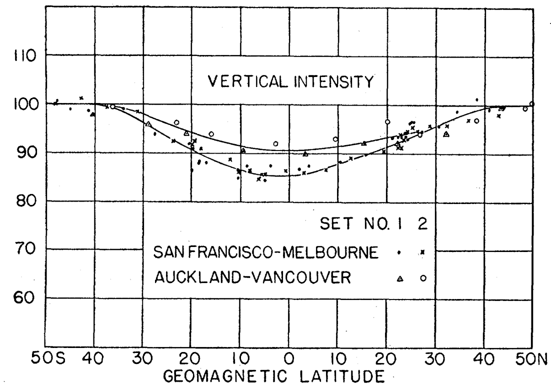

FIG. 4. Relative intensities of vertical coincidences, taken with two different sets of counters, as a function of geomagnetic latitude for two different longitudes.

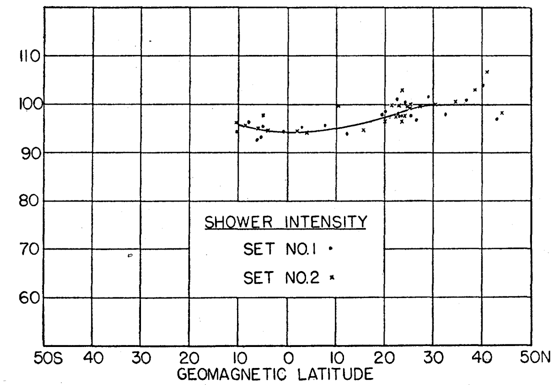

FIG. 5. Relative intensities of showers, taken with two different sets of counters, as a function of geomagnetic latitude from San Francisco to Colombo.

results. Thus, for example, Johnson and Read[1] used an arrangement in which half the rays counted came from a solid angle of $12\times23°$. In our case, as stated above, the corresponding angle is about $20\times55°$.

Considering now the data for the showers, Fig. 5, we first note that in agreement with previous experiments, the latitude effect for the showers is much less than that for the vertical rays. Neither Johnson nor Pickering claim much accuracy for their results but they report effects of 6 percent to 10 percent in South America, and about 6 percent in the Pacific, respectively. The new data show an effect that amounts to about 6 percent on the run to Colombo, although, because of the spread of the points at high latitudes, this result may be in error by a percent or two. However, there is no doubt that the effect is much less than the 14.5 percent observed for the vertical rays in the same region. Regarding the greater spread of points found with the shower data, it is probable that the principal reason for this is statistical. Each point represents less than a tenth as many counts as a point on the curve of vertical counts.

With the experimental evidence thus in favor of a smaller latitude effect for the showers, we now consider the possible explanations of this result. In a sentence the effect can be described as follows: *The latitude sensitive radiation is relatively less effective at producing showers at sea level than the nonlatitude sensitive radiation.*

Now it is known that most of the showers observed below a thin lead plate arise in the lead, and furthermore, in view of the Bethe-Heitler theory, there seems to be good reason to believe that electrons and photons falling on the top surface of the lead produce these showers. If this is the case then the theory at once allows us to conclude that such electrons and photons, in order to cause a shower beneath 1.6 cm of lead must have an energy of the order of 10^9 electron volts. Thus we can say that the coincidences registered with the counters in the shower position give us a measure of the number of electrons and photons present at sea level with energies greater than about 10^9 volts. These electrons and photons of course must be secondaries formed in the atmosphere.

In the light of this discussion the experimental result that the showers show a smaller latitude effect than the vertical rays can be interpreted as meaning that the lower energy charged particles that get in at high latitudes are relatively unable to produce sea level secondaries with energy sufficiently high to register showers. A little consideration will show that such behavior is to be expected for particles that obey the Bethe-Heitler-Oppenheimer theory. For, as a primary passes through the atmosphere its energy becomes divided among a continually increasing number of electrons and photons, and therefore the percentage of the primary energy held by the average secondary decreases as one goes to greater and greater depths. Hence, if the primary has too low an energy it is improbable that any of its secondaries will reach the surface of the earth with an energy great enough to cause a shower to register on the counters. Secondaries may be present to operate the vertical coincidences, but still no showers may be registered. Thus the lowest energy primaries will be inefficient at shower production even though they make their effects felt at sea level.

Let us consider how our hypothesis agrees with experiment. Bowen, Millikan and Neher[7] find that the latitude sensitive radiation, even at sea level, is indeed due to incoming electrons which, at least approximately, obey the theory. Hence the small latitude effect for the showers is consistent with their interpretation of the nature of the latitude sensitive radiation. Another experiment is the variation of the relative numbers of showers and vertical coincidences with altitude. Woodward[8] and others have found that in going to high altitudes the showers increase much more rapidly than the vertical coincidences and although at first sight this appears to contradict our assumption that the highest energy primaries are the most efficient shower producers, it is in fact in agreement with our hypothesis; for clearly, at high altitudes the increase in the energy of the average secondaries will cause a corresponding increase in the probability that the average secondary will cause a shower. Hence the ratio of the number of showers to the number of secondaries will increase with altitude.

A further consequence of this theory is that since an incoming primary must possess a greater initial energy in order to produce a shower at sea level than in order to produce a vertical coincidence, the curve giving the variation of the showers with latitude must reach its constant value at a lower latitude than the corresponding curve for the vertical coincidences. Experimentally this is found to be the case. The "plateau" of the shower curve extends to about latitude 30° as compared with latitude 40° for the vertical coincidences. The energies which can just get in vertically at these latitudes are 9.5 and 6 billion volts, respectively. Hence, in order to produce a shower at sea level, a primary particle must possess an initial energy about 3.5×10^9 volts greater than the energy required to produce a vertical coincidence at sea level. It is perhaps worth pointing out that the conclusion reached by Heitler[9] in a recent paper —namely that the hard band is responsible for the sea level latitude effects, and that the smaller shower latitude effect is due to a smaller shower producing efficiency of the hard band at sea level—is not consistent with this last experimental fact. According to his hypothesis, if the hard band were responsible for both kinds of latitude effect, then the two curves should reach their constant values at the same latitude. Now although it is true that the spread of the points does not allow the shower curve to be drawn very accurately, we believe that there is good experimental evidence of an appreciable difference in the latitudes at which the plateaux set in for the two cases.

Although we have given what appears to be a reasonable explanation of the shower latitude effect, nevertheless this may not account for the whole of the observed effect. Suppose that there is a component of the nonlatitude sensitive radiation which is able to produce higher energy secondaries at sea level than the field sensitive electron primaries are able to do. Then, for this component, it is clear that the ratio of showers to vertical coincidences at sea level will be larger than the corresponding ratio for the electron component, and this again will lead to a smaller latitude effect for the showers than for the vertical rays.

Accordingly we have two mechanisms for producing the smaller sea level latitude effect for the showers:

(1) The requirement of a minimum energy for the electron or photon immediately responsible for the shower.

(2) The possibility that the nonlatitude sensitive radiation contains a component which is more shower producing at sea level than electrons.

In the present state of our experimental knowledge it is not possible to evaluate the relative contributions of these two processes to the observed latitude effect.

The *conclusion* we draw then from the experi-

[7] Bowen, Millikan and Neher, Phys. Rev. **52**, 80 (1937).
[8] Woodward, Phys. Rev. **49**, 711 (1936).
[9] Heitler, Proc. Roy. Soc. **161**, 261 (1937).

mental fact that the showers show a smaller latitude effect than the total radiation at sea level is that the latitude sensitive part of the radiation is much less effective in producing showers at sea level than the nonlatitude sensitive part. This behavior we have shown can be accounted for, at least in part, by assuming that the latitude sensitive component, which consists of incoming electrons, has degraded to such an extent by the time it has reached sea level as to be relatively ineffective in producing showers. The major part of the sea-level showers are therefore due to the nonlatitude sensitive radiation.

We wish to express our appreciation to the Dollar Steamship Company and to Captain Murphy of the President Van Buren, also to the K.P.M. Line and to Captain Blaauboer of the Niew Holland, and to the Canadian Australasian Line for their cooperation and assistance in the experimental work here reported. We also wish to make grateful acknowledgment to the Carnegie Corporation which provided funds that made this work possible.

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Radioactivity in Silver Induced by Fast Neutrons

M. L. POOL*
University of Michigan, Ann Arbor, Michigan

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Radioactive silver, Ag^{112}, has been produced by fast neutron bombardment of Cd^{112} and In^{115}. A half-life period of 3.2 hours is observed with the upper limit of the electron beta-ray spectrum at 2.2 Mev. Gamma-rays are also emitted, the number per beta-ray is about four. The radioactive silver isomer, Ag^{106}, produced by fast neutron bombardment of Ag^{107}, has a positron beta-ray spectrum upper limit of 1.9 Mev and an electron beta-ray spectrum upper limit of 1.3 Mev. The half-life periods are respectively 24.5 min. and 8.2 days. The former emits no gamma-rays other than the annihilation radiation. The latter emits a complex gamma-ray spectrum. The number of gamma-rays per beta-ray is about 35. Nuclear K electron capture is offered to explain this anomalously high gamma to beta ratio. A total of twenty nuclear reactions all leading to the production of radioactive silver have been observed.

INTRODUCTION

THE work with fast neutron bombardment of silver has been continued and the evidence that Ag^{106} is isomeric,[1] yielding two radioactive periods, has been augmented with beta- and gamma-ray measurements. In addition a new period in silver has been found which can be obtained only from cadmium or indium.

There are now a total of six radioactive periods in silver. The finding of the four new periods was made possible by the availability of strong beams of high energy bombarding particles. The two well-known periods in silver, 2.3 min. and 22 sec., were found by Fermi[2] nearly four years ago. He used neutrons from a Ra-Be source and found that slow neutrons were particularly effective in producing the radioactivity.

In this paper it will be pointed out that very fast neutrons, with energies ranging up to 20 Mev, are very effective in producing certain other radioactive periods in silver. However, for the purpose of identification of the radioactive products a routine survey was made with alpha-particles, deuterons, gamma-rays, slow and fast neutrons as bombarding particles on rhodium, palladium, silver, cadmium and indium. In each case the silver precipitate from the chemical separation was measured for radioactivity. As a result, a total of twenty nuclear reactions leading to radioactive silver have been observed.

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* Now at Ohio State University.
[1] Pool, Cork and Thornton, Phys. Rev. **52**, 380 (1937).
[2] Fermi, Ricerca Scient. **5**, 330 (1934).