Yearbook 63 1964

all observatories and shows that the difference from maximum to minimum of the 6-month wave is on the average about 50 per cent of the yearly mean horizontal component, ΔH, from the ERC. This is indeed an unexpectedly large variation. To determine whether these lines indicate that the amplitude of the 6-month wave vanishes at $\Delta H = 0$ (i.e., for zero ERC) requires further statistical analysis, which is in progress. In any event it is clear that the average wave does not vanish for quiet days.

Cosmic-Ray Program

Solar-cycle variation in cosmic-ray intensity and in the equatorial ring current. The H component of the ERC provides a continuous measure of one of the important consequences of solar plasma streams enveloping the earth. Since the streams contain "frozen-in" magnetic fields, the H component of ERC indirectly provides a statistical measure for such fields, which in turn are responsible for most of the important variations of cosmic-ray intensity such as the variation in yearly means of cosmic-ray intensity over the last 2.5 solar cycles which is more closely correlated with the corresponding variation in the H component of the ERC than with any other measure influenced by solar activity.

Observations and reductions of data. Cosmic-ray ionization chambers were operated throughout the report year at Huancayo, Peru, and at Fredericksburg, Virginia. Scalings and reduction of records have been maintained current for both stations.

Cooperation in operation of cosmic-ray meters. Grateful appreciation is expressed to the U. S. Coast and Geodetic Survey and the staff of its magnetic observatory at Fredericksburg, Virginia, for efficient operation of the meters during the past report year, and to the Government of Peru and the Director and staff of the Instituto Geofísico del Peru for making cosmic-ray records from Huancayo available.

Electrical Conductivity Anomalies in the Earth's Crust in Peru

U. Schmucker,[35] *O. Hartmann,*[35]
A. A. Giesecke, Jr.,[36] *M. Casaverde,*[36]
and S. E. Forbush

A cooperative study of geomagnetic variations was undertaken jointly with the Instituto Geofísico del Peru in 1962 and 1963 in central and southern Peru, where nine Askania variographs were installed at temporary stations to investigate the spatial dependence of transient geomagnetic variations. The stations extended from Huancayo, the permanent observatory of the Instituto in the north, to Ayanquera near the Pacific coast in the south, covering about 700 km in the north-south direction (see fig. 49). The station at Cuzco was directly on the magnetic dip equator, which crosses central Peru (see dashed line labeled "inclination = 0°" in fig. 49).

During the International Geophysical Year 1957–1958, Forbush and Casaverde (*CIW Publication 620*, 1961) conducted a survey to study geomagnetic variations from the equatorial electrojet. Some of their survey stations, all near the Pacific coast, are shown in figure 49. During the present survey, in a search for crustal conductivity anomalies, more closely spaced stations were operated within the Andes to study the spatial dependence of short-period variations. The observations were made with battery-operated Askania variographs installed in adobe shelters. Each instrument recorded on 16-mm film the variations of the horizontal (H) and the vertical component (Z) and of declination (D). The time resolution of the records and the temperature insulation of the double-walled adobe shelters allowed the evaluation of variations with periods between 24 hours (daily variations) and a few minutes. All instruments were modified to increase their original Z sensitivities by a factor of about 2.5.

---

[35] Staff Associate.

[36] Instituto Geofísico del Peru.

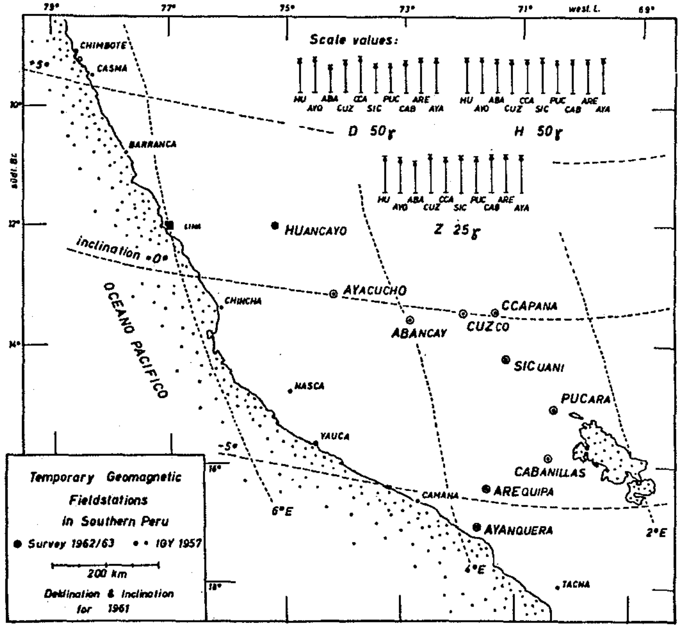

Fig. 49. Temporary geomagnetic field stations in southern Peru.

After various initial difficulties an almost uninterrupted series of simultaneous records from all survey stations was obtained from July to September 1963.

The first objective of the program was to compare simultaneously recorded variations from different sites. As is discussed below, spatial differences of geomagnetic variations within relatively small areas may be used to investigate the electrical conductivity distribution within the earth to a depth of hundreds of kilometers. Local regions of extremely low or high conductivity within the earth's crust and mantle can be found this way.

There is experimental evidence that above several hundred degrees the electrical conductivity of rocks increases rapidly with temperature—by a factor of about 10^4 between 500°C and 1500°C. Furthermore, at very high temperatures the conductivity becomes more or less independent of the specific rock composition, thereby linking conductivity and temperature even more closely. Hence, regional studies of geomagnetic variations and their spatial dependence may lead to useful information about the temperature distribution within the earth in addition to revealing regions of anomalous high or low temperature.

The transient geomagnetic variations observed at the earth's surface consist of two parts, one of external and the other of internal origin. The external part arises from time-varying overhead currents in the ionosphere or beyond; the internal part, from eddy currents within the earth. The eddy currents are electromagnetically induced within the conductive layers of the earth by the time-varying external part. The depth and strength of the eddy currents, and therefore the ratio of the internal (induced) to the external (inducing) part, depend on (1) the conductivity distribution within the earth, (2) the time dependence or period of the transient variations, and (3) the spatial distribution of the inducing external variations.

For rapid variations with periods of less than 1 minute, for example, the induced eddy currents are confined to the uppermost layers well within the geological strata. Slow variations with periods of 1 hour or more will penetrate continental surface layers with little or no attenuation and produce eddy currents at greater depths, where the rise in temperature provides sufficiently high conductivities. Large and deep oceans, however, seem to be conductive enough to shield even long-period variations from the underlying earth's interior.

Thus, the magnetic variations of a certain period as observed at different stations not too far apart should be more or less the same, provided that the overhead currents represent a more or less uniform current sheet above the stations, and the conductivity distribution within the earth is horizontally stratified at the depth where the eddy currents of this particular period flow. If the strength or direction of the overhead currents varies considerably within the range of the stations, the observed variations at the earth's surface will vary from place to place accordingly, not only in their external but also in their internal part. The induced eddy current will follow a pattern similar to that of the overhead inducing currents. If, on the other hand, the flow of the eddy currents is locally distorted by internal conductivity anomalies, only the internal part of the variations will be affected and become "anomalous."

Since the depth of the eddy currents varies with the period of the variations, the frequency dependence of such an "anomalous internal part" can be used to estimate the depth of the distorted eddy-current pattern and thereby of the conductivity anomaly itself. For instance, anomalous variations arising from very shallow conductivity anomalies will gradually diminish for longer periods, since the eddy currents flow at a greater depth, whereas internal variations from deeper conductivity anomalies diminish for shorter periods.

Similar depth estimates can be obtained by studying the anomalous internal part for external inducing fields of various degrees of spatial nonuniformity. An external inducing field with a "spatial" wavelength L decreases proportionally to $\exp(-2\pi z/L)$ downward, where z denotes the depth. The induced field of any induction currents at this depth will then be proportional to $\exp(-4\pi z/L)$ at the earth's surface. Similar considerations apply to the anomalous internal part arising from conductivity anomalies at that depth. The dependence of the internal anomalous part on the ratio z/L permits estimates of z, provided that variations of sufficiently different spatial wavelength can be evaluated. This is possible near the magnetic dip equator, utilizing the highly nonuniform inducing field of the electrojet during the daytime and the more or less uniform inducing field of bays and magnetic storms during the night.

On the basis of these preliminary remarks we shall now examine a number of simultaneously recorded magnetograms from the survey stations. The curves in figures 51 and 52 are tracings of magnified images from the original 16-mm film. The curves are arranged for each component separately, and the scale values for Cuzco are indicated by arrows at the margin. The scale values of the remaining stations, which are nearly the same, are shown in figure 49. The full circles on the small maps in figures 50, 51, and 52 indicate operating stations, and the dotted line in figures 50 and 51 shows the dip equator.

It is well known that during the daytime all ionospheric current systems near the equator are pinched together within a narrow latitude zone just above the magnetic dip equator. This equatorial current concentration or "equatorial elec-

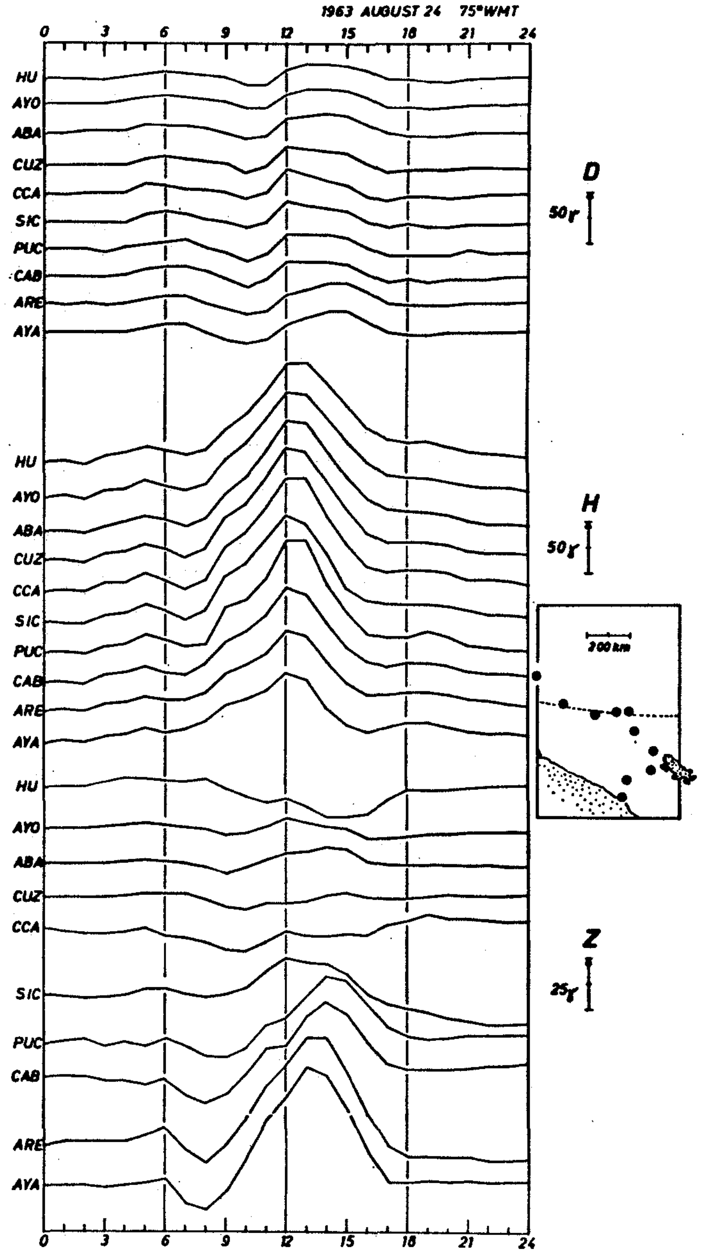

Fig. 50. Diurnal variations on a magnetically quiet day; increasing noon maximum in H toward the dip equator (CCApana, CUZco), and positive Z peak at the southern survey stations (AREquipa, AYAnquera) due to the equatorial electrojet.

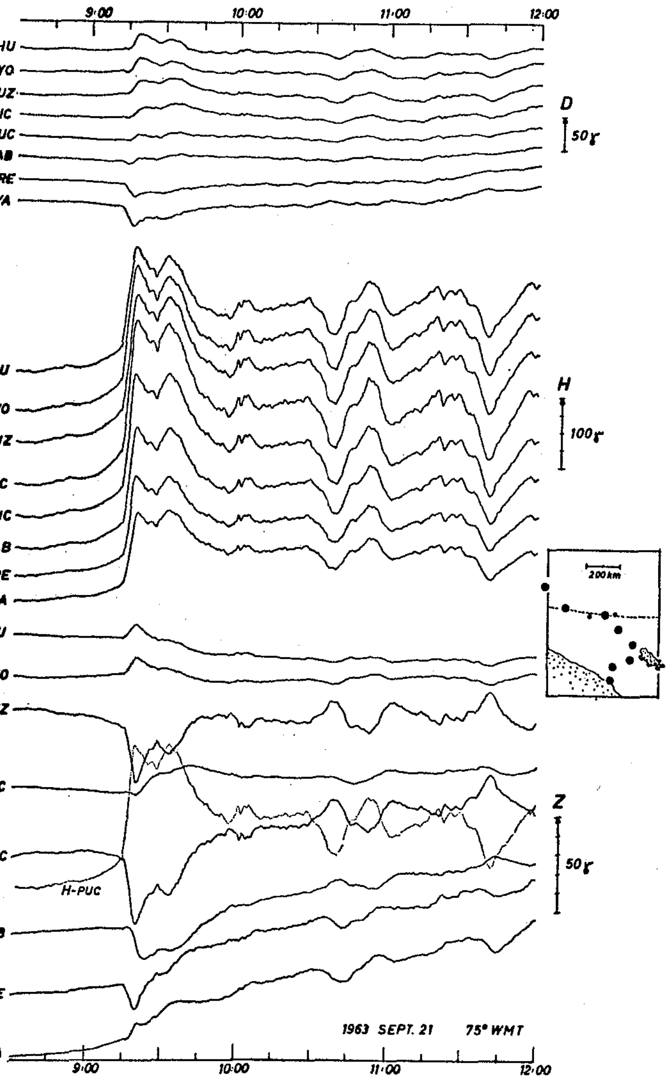

Fig. 51. Sudden storm commencement (ssc) during the daytime and subsequent short-period fluctuations; increasing amplitude of the *H* variations toward the dip equator indicates electrojet effect on these short-period variations. The *Z* variations, however, change irregularly from place to place and are obviously affected by internal conductivity anomalies, especially at CUZco and PUCara.

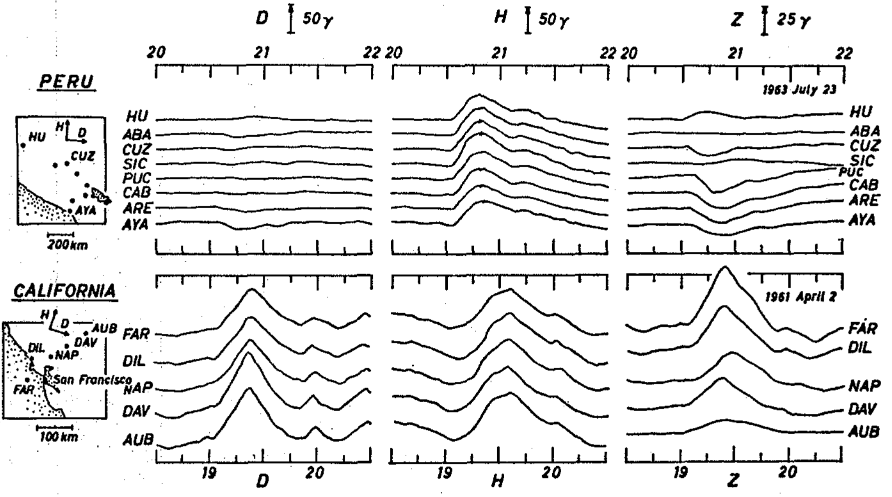

Fig. 52. Night-time bay disturbances: The lower curves for California show the "normal" coast effect with Z variations, pronounced near the coast and diminishing inland, which are similar to the variations in D and H and thus to the variation in the component perpendicular to the coast. At AYAnquera, on the coast of Peru, a "reversed" coast effect is shown by the Z variation which is opposite to that in the component H perpendicular to the coast. Apart from the reversed coast effect, the similar H variations at stations in Peru and the dissimilar anomalous Z variations, especially for the four upper curves, are evident.

trojet" is clearly visible from the records of daytime variations.

Figure 50 shows the daily variations of a magnetically quiet day as obtained from readings every hour on the hour. The steady increase of the noon maximum in H from Ayanquera, 400 km to the south of the dip equator, to Cuzco, right on the dip equator, demonstrates the effect of the equatorial electrojet which is superimposed on the normal S_q current system.

The small Z variations at the equatorial stations (Ayacucho, Abancay, Cuzco, Ccapana) and the southward increasing midday Z peak at the southern stations correspond well with an overhead equatorial electrojet. The expected negative Z peak north of the dip equator is already visible at Huancayo. Forbush and Casaverde found during their more extensive survey that the maximal negative Z peak at noon occurs about 350 km north of the dip equator at Chimbote (see fig. 49).

The nearly perfect correspondence of H and Z to an overhead equatorial electrojet indicates that any contributions from induced eddy currents to the observed variations are rather small. Hence, these currents must flow at great depth. Forbush and Casaverde estimated this depth to be 250 km or more. Because of the small effect of the induced currents on the observed variations it is difficult to decide whether the internal part of the variations is normal or affected by conductivity anomalies at the depth stated above.

Figure 51 shows the first few hours of the most intense magnetic storm of 1963, which started on September 21 at 9^h15^m with a sharp sudden storm commencement (ssc) and lasted for 2 days. Fortunately, this storm was recorded at all survey stations except Abancay and Ccapana. As seen from the curves in figure 51, the H amplitude of the ssc and the amplitude of the subsequent short-period variations increase gradually toward the dip equator, indicating a similar equatorial concentration of the overhead currents as already described for the long-period daily variations. It might be added that the electrojet for short-period variations appears to be more concentrated than the electrojet for daily variations. The Z variations, however, differ distinctively from place to place and do not reflect at all the external electrojet field. Large Z variations reversed to those in H appear at the equatorial stations Cuzco, where there should have been none, and Pucara, 175 km farther south. But these clearly anomalous Z variations are absent at Sicuani, halfway between Cuzco and Pucara. Neither Huancayo in the north nor Ayanquera and Arequipa in the south show the Z variations as expected from the equatorial electrojet. This behavior indicates that the external part of the Z variations is compensated by an equivalent internal part due to induction currents very close to the surface. All stations seem also to be affected by conductivity anomalies.

A careful study of many similar daytime variations confirmed that Z and H preserve at each site the characteristic relation to one another seen in figure 51. The anomalous behavior of the short-period daytime variations in Z on a rather local scale and the compensation of the external electrojet variations lead to two conclusions: the induction currents flow very close to the earth's surface; and their current pattern is highly distorted by an irregular subsurface conductivity structure. Sicuani, for instance, seems to be within an area of flat subsurface conductivity distribution; Pucara and Cuzco, above zones of great conductivity contrasts. The small number of survey stations, however, does not permit the reconstruction of the distorted pattern of the eddy currents, and it can be concluded only that the subsurface conductivity structure in southern Peru must be very complicated.

It might now be argued that the eddy currents flow directly within the surface layers and that their distorted pattern reflects the complex surface geology of southern Peru. If this interpretation were correct, anomalous variations, especially in Z, should be found at the coastal station Ayanquera, where the poorly conductive volcanic and metamorphic rock formations along the coast come together with the highly conductive Pacific Ocean. This anomaly does not seem to exist.

On the other hand, the depth of the induction currents for short-period fluctuations during the day must be small in comparison with the half-width of the electrojet field, which in Peru, according to Forbush and Casaverde, is about 350 km. Hence, these currents seem to flow within the upper 50 km and therefore at a shallower depth than would be expected from observations in other parts of the world. Southern Peru as a whole appears to be an anomalous area, where the conductivity increases with depth more rapidly than elsewhere.

The absence of any pronounced coastal anomaly of the Z variations is remarkable in itself. There is evidence that worldwide variations with periods of several hours or less produce strong oceanic induction currents. These currents do not penetrate into the continental surface layers where large and deep oceans are bound by shorelines unless the period of the inducing field is of the order of a few minutes. Hence, in the period range from a few hours to a few minutes the currents are forced to flow parallel to the shorelines, thereby producing anomalous internal variations, especially in Z. This coastal "edge effect" has indeed been proved by Parkinson (*Geophys. J.*, *6*, 441–449, 1962) for many coastal observatories around the world. He also showed that the anomalous Z variations at the coast are linearly correlated to the horizontal disturbance vector H_s, transverse to the trend of the coast pointing inland, the ratio $Z{:}H_s$ being about 1:2. The correlation simply implies that the duction currents flow parallel to the ast and that they are more or less in hase with the inducing external field. vestigations by Mason (*Trans. Am. eophys. Union*, *44*, 40, 1963) on several acific islands revealed a similar "island fect" due to the deflection of oceanic duction currents around poorly con- uctive islands.

Since in southern Peru the trend of the astline is about perpendicular to the rection of H, we would expect pro- unced Z variations parallel to those in at Ayanquera and smaller ones at requipa and Cabanillas. This coastal omaly has not been found, even though e Pacific Ocean is extremely deep here. ne possible explanation of the missing omaly would be that the equatorial ectrojet (even though part of a world- ide current system) provides an induc- g field of only small spatial dimensions. ts limited extent might so reduce the trength of the oceanic induction currents hat the coastal anomaly became insig- ificant. The correctness of this explana- ion can be tested by examining the ehavior of night-time variations near the oast. Such variations arise from world- ide overhead currents in connection ith disturbances in the auroral zone. As here is no electrojet effect at night, it is easonable to assume that the night-time urrents are fairly uniform in equatorial egions.

The upper part of figure 52 shows a ypical night-time bay disturbance in Peru. Comparing the traces among the arious survey stations we find consider- ble uniformity among the H variations ut again a quite anomalous behavior of Z. A slight but steady increase of the bay n H from Ayanquera toward Sicuani night indicate a faint night-time electro- jet. However, it is thought to belong to the internal part.

If the conductivity distribution were horizontally stratified, the Z variations would be nearly zero at all stations, because of the uniformity of the inducing field. But we find a positive bay in Z at Huancayo, reversed Z variations at Cuzco and Pucara, and none at Sicuani. All this is more or less identical with the behavior of the Z variations during the daytime, except that the southern stations, Cabanillas, Arequipa, and Ayanquera, show their anomalous part much more clearly than during the daytime, when it is masked by the external electrojet field. The agreement between day and night-time effects is another indication that the distorted induction currents flow at a very shallow depth as compared with the half-width of the electrojet. Otherwise, the anomalous Z variations would have been much smaller during the daytime than during the night because of the decrease of the electrojet field downward.

At Ayanquera and Arequipa the negative Z variations, even for bays, are opposite in sign from those due to the usual coastal anomaly. As an example for the expected "normal" coastal anomaly, figure 52 presents the traces of a bay disturbance from a similar survey in California. We notice here pronounced Z variations at the coast, parallel to those in H and D, which combined form the horizontal disturbance vector perpendicular to the coastline. These anomalous Z variations gradually diminish inland and disappear about 150 km from the coast, a distance corresponding to the depth of the induction currents below the continent in California (*J. Geomag. Geoelec. Kyoto*, *15*, 193–221, 1964). The absence of such an anomaly in Peru implies again that a highly conductive substratum comes close to the surface, thereby damping the oceanic induction currents and likewise reducing the coastal anomaly. Furthermore, the negative Z variations at the coast suggest that the depth of the subsurface induction currents increases toward the ocean.

More observations and a thorough analysis of the data combined with theoretical work will eventually lead to a more quantitative description of the complicated conductivity structure in southern Peru. It is of course tempting to interpret the unusual high conductivity at a shallow depth by an unusual high temperature gradient under southern Peru, reflecting the volcanic and tectonic activity of this area. It would be even more desirable, however, to find supporting evidence for deductions of this kind from other geophysical observations.

Acknowledgments. We express grateful appreciation to the U. S. Coast and Geodetic Survey for the loan of the Askania variographs for this study and to the National Science Foundation for their generous grant to the Instituto Geofísico del Peru in partial support of this work. The stations at Abancay, Cuzco, Sicuani, Pucara, and Cabanillas were operated by Mr. Velasques (Instituto Geofísico del Peru), the one at Ayacucho by Mr. Castillo (Instituto Geofísico del Peru), and those at Arequipa and Ayanquera by Messrs. Tamayo and Corso (Universidad Nacional de San Agustín, Arequipa).

LABORATORY PHYSICS

NUCLEAR PHYSICS

L. Brown, H. Christ,[37] *H. Rudin,*[37] *and H. R. Striebel*[38]

Polarized Ion Source

The Basel source of polarized ions and the Carnegie electrostatic generator yielded new information about the spin interactions in the $\mathrm{He}^3(d, p)\mathrm{He}^4$ reaction during the past year. An experimental study of the effect of tensor polarization as a function of energy was suggested by Professor L. J. B. Goldfarb of Manchester, who is examining it theoretically. The measurements as originally planned are well advanced, and the study has been expanded to include the effects of vector polarization as well. Investigation of those effects is possible because of the successful modification of the ionizer of the source to allow the axis of spin to be oriented in any one of four directions relative to the direction of the beam. A gratifying aspect of the work on $\mathrm{He}^3(d, p)\mathrm{He}^4$ is a measure of P_{33}, the component of the tensor describing the deuteron beam, at the very broad S-wave resonance at 430 kev. Ideally our ion source should produce a beam with $P_{33} = -\frac{1}{3}$; the value given in last year's report ($P_{33} = -0.266 \pm 0.011$) was measured at 700 kev, as the high-voltage machine was unstable at lower energies. Since then we have learned to operate the generator so as to excite the reaction near its resonance, and we now have a value of $P_{33} = -0.304 \pm 0.005$, a large part of the discrepancy between theory and last year's experiment being the result of the energy variation of the reaction.

We have also measured P_{33} with the $T(d, n)\mathrm{He}^4$ reaction, the mirror image of the He^3 reaction, obtaining a value of -0.301 ± 0.009. This is reassuring both of the correctness of our measurement method, since the detection of neutrons involves techniques entirely different from those used for protons, and of the predicted identity of the behavior of the two reactions. It is a clear-cut demonstration that the forces between nucleons are independent of the charge.

The measurements of $\mathrm{He}^3(d, p)\mathrm{He}^4$ for deuteron energies up to 3140 kev are reported as three quantities defined in a manner convenient for comparison of experiment and theory. Consider a right-handed, center of mass coordinate system with its positive z axis parallel to the propagation of the polarized ion beam and its origin at the target. The polarized ion source furnishes, to the best of our knowledge, a beam described by one component of a vector, P_3, and three components of a tensor, $P_{33} = -2P_{11} = -2P_{22}$, where the subscripts 1, 2, 3 represent a right-handed coordinate system

---

[37] Carnegie Institution Fellow and Fellow of Swiss National Foundation; from University of Basel.

[38] Carnegie Institution Fellow; from University of Basel.