POLARIZATION OF RADIO PULSES FROM EXTENSIVE AIR SHOWERS*

W. E. Hazen, A. Z. Hendel, Howard Smith, and N. J. Shah
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan
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We have used log-periodic, EW- and NS-arm antennas to investigate whether radio pulses from extensive air showers are polarized perpendicularly to the earth's magnetic field. Up to three such pairs of antennas were operated simultaneously, and 32 events with 84 radio pulses were observed. In the polarization part of the experiment, there were 23 pulses recorded in EW antennas versus 7 in NS, suggesting some geomagnetic production of radio pulses.

Radio pulses from extensive air showers have been detected by several groups[1-6] and the production mechanism has been investigated by several authors.[1,7-10] Kahn and Lerche,[7] in particular, predicted that the earth's magnetic field plays an important and probably dominant role, separating positrons and electrons. The resulting displacement current and the resulting dipole would produce a radiation polarized perpendicular to the earth's magnetic field. Another mechanism is based on the negative-charge excess due to positron annhilation in a shower front. This mechanism would produce a radially polarized radiation.

Our experiment was designed to investigate the polarization of radio pulses by means of antennas whose arms were aligned NS and EW respectively. The location of our experiment (at Mt. Chacaltaya, Bolivia, near the geomagnetic equator) was particularly favorable since the geomagnetic field is nearly horizontal and thus allows good symmetry with respect to the zenith between the patterns of two vertical antennas with different arm orientations. The Bolivian Air Shower Joint Experiment (BASJE) scintillator array provided the trigger and information about shower arrival direction, core location, and size. We used log-periodic antennas, most of them designed for 50-90 MHz. The overall frequency response of our channels was about 50-70 MHz, except for two channels with antennas with longer arms in the second part of our experiment. Our antennas had median-frequency half-power beamwidths of 75° in the E plane (plane of the arms) and 110° in the H plane.

An "event" was a shower that produced a radio pulse in at least two antennas at the "right" time. The requirement of two simultaneous pulses was necessary since the arrival-time distribution of pulses in each antenna was not well peaked at the "right" time. However, the probability of a chance coincidence of two pulses at the right time was negligible. The right time of arrival of the radio pulse depends on the arrival direction of the shower, since the arrival times were measured with respect to the arrival of the shower particles at the center of the scintillator array. Our antennas were about 50 m from the center of the scintillator array, and therefore showers with different arrival directions could arrive at the antennas before or after they reach the center of the array. The "right" time thus refers to the arrival time corrected for the arrival direction effect.

The first part of our experiment was carried out with four antennas, three of which were inclined at a zenith angle of 40° towards the west. The asymmetry in directional sensitivity of inclined antennas allowed us to use the independently measured shower-arrival directions as a powerful tool to confirm the identification of radio pulses.[5] All but 3 of the 20 recorded events arrived from the western hemisphere, confirming that the radio pulses were associated with showers. Since log-periodic antennas were used in this experiment for the first time, this new confirmation was important.

Two of the inclined antennas in this first part were identical, except that one had its arms EW and the other NS. If radio pulses were produced by the geomagnetic mechanism only, no pulses would be expected in the NS antenna. There were 19 pulses in the EW antenna and 8 in the NS antenna, but this does not indicate a predominance of EW polarization since each event required at least 2 pulses and both auxiliary antennas were oriented EW. In fact, the observed result would be expected even with random polarization.

In the second part of our experiment we used paired EW and NS antennas to investigate polarization further. Six vertical log-periodic antennas were used. Since the cosmic-ray rate depends only upon the zenith angle, the number of showers within the pattern of a vertical antenna is independent of the orientation of its arms. Two double-bay JFD Model No. LPV-TV100 antennas were arranged in a square, one with arms NS and the other EW. The double-bay geometry makes the antenna cones nearly circular by reducing the H-plane beamwidth. Thus nearly all showers within the pattern of the EW antenna are also within the pattern of the NS antenna. Two single-bay log-periodic JFD Model No. LPV-TV130 antennas were also oriented NS and EW, respectively. A third pair of antennas with longer arms was also oriented NS and EW. During part of the time, only two antenna pairs were operating.

Of 12 recorded events, 11 events and 23 pulses were in EW antennas versus 6 events and 7 pulses in NS antennas. There was only 1 event with pulses in more than one NS antenna, whereas there were 10 such events in EW antennas, of which two had pulses in all three EW antennas and three had pulses in all two operating EW antennas. There were 6 events with 2 or 3 pulses in EW antennas and no pulses in NS antennas, whereas there was only 1 event without a pulse in an EW antenna, and this event had pulses in both operating NS antennas.

Thus, there were more pulses in EW antennas, suggesting some geomagnetic production of radio pulses. This result agrees in general with results of other experiments.[6,11-13] However, there may be a disagreement with the Haverah Park, England, group[13] regarding frequency dependence. [The Haverah Park group is a collaborative effort among the universities of Bristol, Durham, and Leeds and Imperial College (London)]. Their preliminary results show that the geomagnetic effect becomes less important with increase in frequency from 32 to 44 MHz, whereas the present results, for frequencies of 40-50 MHz and up, indicate that the geomagnetic effect is not negligible.

The simultaneous operation of several channels including the first part with inclined antennas, showed 12 events with pulses in three antennas with parallel arms (all EW), but also 19 events with no pulse in one or more EW or NS antennas, while other parallel antennas did show pulses. The maximum separation of our antennas was 60 m. We also operated two antennas with EW arms at a separation of 3 m and in this case the correspondence was good in 6 out of 7 observed events. In general, it was not the antenna nearer the shower axis that showed a pulse. This apparent anomaly, which may disagree with the results of Vernov et al.,[4] will be further investigated.

As in a previous experiment[5] the radio showers were larger on the average than all showers. The median size of all showers that triggered our array was 10^7 particles, whereas the median radio-shower size was 6×10^7. The cores of the radio showers fell preferentially in the half of the BASJE array where the antennas were located. Twice as many shower cores were in the antenna half as in the opposite half.

There is evidence that the pulses in the NS antennas cannot be explained by radially polarized radiation: (1) According to the calculations of Kahn and Lerche,[7] the radial polarization would be effective only at a distance greater than about 100 m from the shower axis. But of the events with pulses in the NS antennas, two-thirds had cores at less than 100 m from the antenna. This ratio is the same as that for all radio showers. This shows that events in NS antennas are not associated with larger core distances than events in EW antennas. (2) The E vector of events with pulses in the NS antennas in the radial hypothesis shows no predominance in the NS direction.

The pulses in the NS antennas cannot be due to accidental coincidences (as explained above), but they may be interference pulses picked up simultaneously by several antennas. An analysis of pulses on our traces outside the "right" time shows that this is very unlikely, but further analysis of this point is in progress.

The total running time was 3500 h, but the events were not randomly distributed in time. For instance, the first part of the experiment ran for 800 h and had 23 events; the second part ran for 2700 h and had only 36 events. We are now investigating possible reasons.

The radio showers in this experiment were selected because radio pulses in at least two antennas were associated with them. However, they also differed from all showers in the following three ways: (1) In the first part, almost all radio showers arrived from the west, the direction in which our antennas pointed. (2) The median radio-shower size is six times that of the size of all showers. (3) The radio-shower cores arrived predominantly near the antennas. These differences between the radio showers and all showers made it unlikely that our events are spurious.

Paul R. Barker, deceased, participated in earlier experiments and built part of the equipment used in this experiment.

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GENERALIZATION OF VENEZIANO'S FORMULA FOR THE FIVE-POINT FUNCTION*

M. A. Virasoro
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
(Received 25 November 1968)

We generalize Veneziano's formula for the five-point function by writing an integral formula on a two-dimensional space and imposing on it the requirements implied by crossing symmetry, analyticity, and Regge behavior.

Almost immediately after the first explicit formulation of the "duality mechanism,"[1] its application to production processes was proposed[2] to explain the resonance-Deck-effect controversy over the A_1 peak. Recently Veneziano[3] found a very simple expression which incorporates this principle together with Regge behavior, crossing symmetry, and analyticity for the scattering amplitude of two particles going into two particles. Up to now the experimental tests[4] show that these kind of representations reproduce the real world to a rather good approximation. The importance of generalizing them to the five-point function seems then quite obvious. Let us only say that if obtained, it will give the correct prescription to treat overlapping resonances in final-state interactions and will give a complete solution to the bootstrap based on superconvergence of the reaction $P+P\to P+X_J$.[5]

In this Letter we want to show how this generalization is possible. We begin by considering the integral representation for one term of Veneziano's formula,

$$V(s,t)=\int dx(1-x)^{-\alpha(t)-1}x^{-\alpha(s)-1}. \qquad (1)$$

For a five-point function the number of independent variable is five while the number of variables connected by crossing symmetry is ten. In analogy to Veneziano's method (see, however, the paper by Virasoro[6] for an alternative way of imposing crossing symmetry) we suppose that the scattering amplitude can be written as

$$\sum_{ijklm} V(s_i,s_j,s_k,s_l,s_m), \qquad (2)$$

where the sum is over all possible sets of five independent variables.

Once a set of s_i is chosen we order the particles in such a way that each s_i corresponds to the square of the total momentum of two adjacent particles and then redefine the particles as shown in Fig. 1. The only crossing symmetry that must be satisfied by each term V in (2) is then with respect to the transformations $s_i\to s_{\pm i\pm 1}$