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RADIO PULSES AND THE DETECTION OF LARGE AIR SHOWERS*

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Radio pulses can be used to measure the arrival directions of large cosmic-ray air showers. Since nearly all very large showers and nearly all large zenith-angle showers had detectable radio pulses, the method shows promise for the detection of such showers.

The study of radio pulses from air showers can be divided into two broad categories: the investigation of the mechanism of radio pulse production and the use of radio pulses as a tool for shower detection. We will address ourselves mainly to the second category: Can radio pulses be used to measure very large air showers? The question can be divided into four parts: (A) Can air-shower radio pulses be distinguished from background? (B) Does a sufficiently high proportion of showers have detectable radio pulses? (C) Can the arrival direction be found? (D) Can the core location and the size of each shower be found? We report here measurements that show affirmative answers to the first three questions.

Radio pulses have been observed in association with air showers at Mt. Chacaltaya, Bolivia (altitude 5200 m, geomagnetic latitude 4°S). The Bolivian Air-Shower Joint Experiment (BASJE) array now consists of five scintillation detectors on a circle of 150 m radius and of a cluster of detectors at the center of the circle. Five additional detectors are designed to determine shower arrival directions from particle arrival times. For our study of radio pulses associated with air showers, the BASJE array was triggered whenever there were more than 25 particles in any two of the outer circle detectors and in the center detector. The trigger rate was 3.6/h. For each shower the BASJE particle data allow us to determine arrival direction, core location, and size. Radio pulses were detected with seven log-periodic antennas. The antenna arms were placed in an EW plane, since previous experiments[1,2] had shown that EW polarization predominates. The half-power cone of our antennas was 75×110°. The position of the antennas is shown in Fig. 1(a). For most of the time, the antennas were pointed west at a zenith angle of 45°. After suitable delays, the signals were displayed on separate oscilloscope traces. Near the end of each trace there were delayed timing reference pulses that marked the arrival of the particle front at the center of the BASJE array. Radio-pulse arrival times were measured with respect to these timing pulses. The rf pass band was 54-88 MHz, but delay lines limited the post-detector bandwidth to no more than 15 MHz.

The following preliminary results are based mainly on 87 radio showers collected over a three-month period, with pulses greater than twice the average noise level in three or more channels. All but two of these showers arrived from the west as expected for our west-pointing antennas. A group of 200 showers from an earlier run was used as the "parent population", that is, as a reference sample, in this preliminary analysis.

When a pulse arrives at an antenna within a few nanoseconds of the arrival of the shower particles, we have a candidate for a radio shower. Since the antennas are ≥50 m from the center of the array, the shower front will arrive at each antenna earlier or later than at the center of the array, depending on the inclination of the front. Therefore, we computed a corrected arrival time for each pulse in each antenna, taking into account the particle arrival direction and the position of the antenna. Histograms of the corrected arrival times allow us to determine the probability that a given pulse was produced by a shower rather than background. Of our seven channels, one consistently showed less background than the others. In one period of three weeks all channels showed less background than in other periods. However, when coincidences of pulses in two or three channels are required, the histograms have good peaks regardless of the performance of the individual channels.

Figure 2 shows histograms of pulse arrival

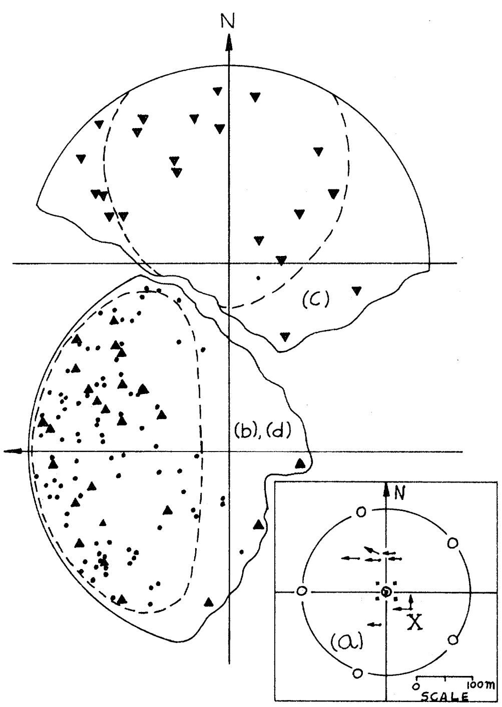

FIG. 1. (a) The BASJE scintillator array, with density detectors (open circles) and timing detectors (closed squares) and the position and orientation (arrows) of the seven antennas used in this experiment. Antenna X was used for the arrival directions shown in (b) and (c). (b), (c) Arrival directions of radio showers when antenna X was pointed at a zenith angle of 45° W (closed triangles) and when it was pointed North (closed inverted triangles). The half-power antenna patterns (dotted lines) are also shown. (d) Arrival directions of 87 radio showers with pulses in at least three antennas (closed circles).

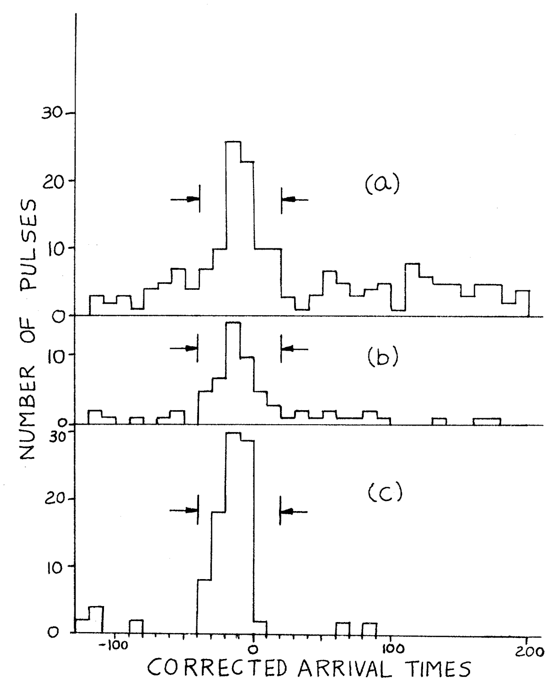

FIG. 2. Histogram of corrected radio pulse arrival times (a) for pulses in antenna X, (b) for coincidences of pulses in antenna X and any other antenna, and (c) for coincidences in any three antennas. The unit of time is 10 light-meters (1/30 μsec). The origin is at the computed arrival time of the particle front.

times (a) for our best channel alone, (b) for coincidence of radio pulses in two channels, and (c) for coincidences in any three channels. These histograms show that, if we define radio showers as those having pulses in the bracketed time intervals, we would expect about 28%, 16%, and 1.1% spurious events, respectively. If we had no setup to measure arrival directions from particle data, we could not compute corrected times. We have therefore redrawn the above histograms with uncorrected times and then the respective percentages of spurious events were greater: 43%, 24% and 2.2%. The requirement of a triple coincidence thus allows the identification of a radio shower on an individual basis.

Radio showers thus identified differ from the parent population in shower size, zenith angle, and arrival direction. Figure 3(a) shows the ratio of radio showers to parent showers as a function of shower size and Fig. 3(b) as a function of zenith angle. Figure 3(a) shows that the proportion of radio showers is proportional to the shower size and approaches 100% near a size of 10^9 particles. Figure 3(b) shows that the proportion of radio showers is proportional to $[\cos(\text{zenith angle})]^{3.2\pm0.4}$ and approaches 100% near 75°. The zenith-angle dependence is not related to the shower-size dependence since for our radio showers there was no correlation between zenith angle and shower size.

The most striking difference between radio showers and the parent showers is in the arrival direction of radio showers. In most of our present experiments, all antennas were inclined at about 45° toward the west, but for three weeks we inclined the antenna in our best channel (antenna X) toward the north. The results for this antenna alone are shown in Figs. 1(b) and 1(c). The parent showers (not shown) arrived from directions symmetrical about the zenith but detected radio showers arrived predominantly in the half-power cone of the antenna, from the west when the antenna pointed west and from the north when it pointed north.

The arrival directions of the 87 triple-pulse events are shown in Fig. 1(d), together with the half-power antenna pattern. The fact that only two events lie in the eastern hemisphere, far from the half-power cone, is consistent with our previous conclusion that the background contamination of our events is only about 1%.

These results show that we can correctly identify the radio pulses from air showers and that large showers and showers at large zenith angles

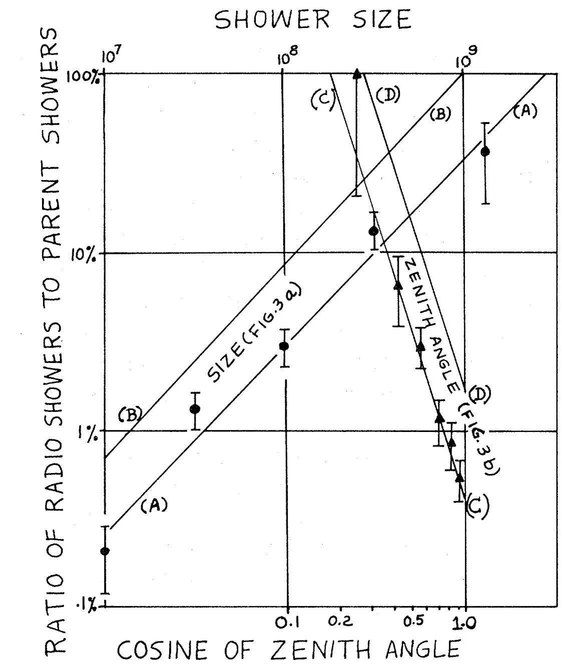

FIG. 3. (a) Ratio of radio showers to all parent showers as a function of shower size (A), and (B) ratio of radio showers to those parent showers within the half-power cone of the antenna pattern [shown in Fig. 1(d)]. (b) Ratio of radio showers to parent showers as a function of zenith angle (C). Same ratio but within the half-power cone (D).

have a high probability of producing radio pulses.

For the measurement of shower arrival directions we required a minimum distance (d) of 50 m as a base line and we had a maximum distance of 150 m between the most distant antennas. Only in 14% of our events could the arrival direction be measured from the arrival time of three or more radio pulses alone, and in another 43% the arrival time of the pulse in the scintillator at the center of the array was used in addition to those in two antennas. Figure 2(a) shows that the measured arrival time (t) had a standard deviation (dt) of 40 nsec. Since the uncertainty in the angle (θ) between the shower arrival direction and any base line is $d\theta = cdt/d(\sin\theta)$, the maximum accuracy for our antenna spacing of 150 m is about ±5° but the accuracy is much worse for shorter base lines and for smaller angles θ, which are common at large zenith angles.

The arrival directions found from radio pulses were compared with those computed from particle data and the agreement was as good as expected from the above estimate of accuracy. Thus, the arrival directions can be measured from radio pulse arrival data. Furthermore, this result shows that there is a well-defined radio shower front. This front may precede the particle front by about 15 m, on the average (Fig. 2), but the possible systematic error is also 15 m.

Although we used the particle arrival directions to study the background, the identification of radio showers can be made without reference to it. Thus, we do not need the BASJE fast-timing array. We do need some particle detectors, however, to provide the trigger pulse and the timing reference pulse.

We also attempted to trigger on a coincidence of radio pulses in three antennas without a particle requirement. In addition to interference triggers, we obtained several good triggers per hour, most of which showed not only clean pulses in the three required antennas but also coincident pulses in one or more other antennas. All pulses were consistent with production by a single electromagnetic wave front. We are now studying the possibility that these events were in effect produced by extinct, near-horizontal showers.

The first three conditions for using radio pulses to measure large air showers can be met, according to the above results. On the other hand, no good correlation was found between pulse heights and such shower parameters as size and core distance. Thus, at present we can determine neither the core location nor the size of a shower from radio-pulse data alone. However, for some studies these data are not necessary. For example, the celestial arrival directions of large radio showers can be measured with our present radio-pulse techniques.

On the other hand at sea level, Vernov et al.[3] have evidence for a dependence of radio pulse heights on muon numbers and also on the distance from shower axis, promising a possible solution to part D of the problem of radio-pulse measurement of air showers.

At sea level, Allan, Jones, and Neat[4] have found increases in the proportion of radio showers both as a function of shower size and as a function of zenith angle, similar to our results.

This experiment would not have been possible without data from the BASJE group whose efforts in Bolivia were directed by Dr. K. Kamata, Dr. M. Lapointe, Dr. K. Murakami, Dr. S. Shibata, Dr. K. Suga, and Dr. Y. Toyoda.

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PROTON-NEUTRON SCATTERING

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Using Glauber multiple-scattering theory, the missing-mass spectrum for protons scattered off a deuterium target is computed. The relatively clean separation of the single- and double-scattering peaks offers the possibility of determining the high-energy proton-neutron differential cross section.

Experimental data on proton-proton elastic scattering at high energies show angular distributions with interesting structure.[1] It is therefore natural to ask if similar features are present in the neutron-proton case. Unfortunately, cross-section measurements with neutron beams[2] are very imprecise, especially at the larger angles $[|t|>1\ (\mathrm{GeV}/c)^2]$. In the absence of a free-neutron target, it has recently been suggested that the proton-neutron cross section can be deduced from observations of quasielastic scattering in proton-deuteron collisions.[3]