First Experimental Characterization of Microwave Emission from Cosmic Ray Air Showers

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We report the first direct measurement of the overall characteristics of microwave radio emission from extensive air showers. Using a trigger provided by the KASCADE-Grande air shower array, the signals of the microwave antennas of the Cosmic-Ray Observation via Microwave Emission experiment have been read out and searched for signatures of radio emission by high-energy air showers in the GHz frequency range. Microwave signals have been detected for more than 30 showers with energies above 3×10^{16} eV. The observations presented in this Letter are consistent with a mainly forward-directed and polarized emission process in the GHz frequency range. The measurements show that microwave radiation offers a new means of studying air showers at $E \geq 10^{17}$ eV.

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Introduction.—At energies above 10^{15} eV, cosmic rays can be measured only indirectly by studying the extensive air showers they produce in Earth's atmosphere [1]. Different techniques have been developed to measure air showers with instruments of large aperture. While arrays of particle detectors on the ground can only sample the shower at one particular depth in the atmosphere, optical detectors allow the measurement of the evolution of the shower, including the depth profile of the number of shower particles in the atmosphere. Optical methods have the advantage of providing a calorimetric measurement of the shower energy and, through determining the depth of shower maximum, also a good estimate of the type or mass of the primary particle. On the other hand, they can be applied only in dark nights and good atmospheric conditions, limiting the duty cycle to typically less than 15%.

Since the pioneering studies in the late 1960s [2], it has been known that extensive air showers produce electromagnetic pulses in the kHz and MHz frequency ranges. Similar to optical measurements, the radio signal of an air shower gives access to the longitudinal shower profile and, hence, the primary shower energy and particle type and mass [3–7]. Moreover, it is possible to use the radio detection technique with almost 100% duty cycle. Therefore, with the availability of suitable electronics and improved shower simulation methods [8–11], the study of radio emission by air showers has been receiving increasing attention in recent years [12–15].

Extensive air showers consist of a disk of high-energy particles traversing the atmosphere. With the thickness of this disk being of the order of 1 m up to tens of meters from the core, charged particles emit electromagnetic waves coherently, mainly at frequencies below about 100 MHz, corresponding to a wavelength of 3 m. However, large-scale exploitation of this signal and, in particular, triggering on the radio pulses directly, is hampered by considerable background radiation from natural sources and a significant amount of transients in this frequency range due to anthropogenic sources.

In comparison, observations in the lower GHz (microwave) range would have significant benefits. First, the background noise is extremely low at these frequencies and the atmosphere is almost perfectly transparent for such waves, nearly independent of cloud coverage. Second, reliable low-noise receiver systems are commercially available because they have been developed and refined for satellite TV antennas for many decades.

Until recently, radio emission from air showers at GHz frequencies has not been considered as a promising detection channel as the wavelengths are much smaller than the typical size of the shower disk. Early measurements covered only frequencies up to 550 MHz and showed a strong, exponential suppression of higher frequencies [16–19]. However, during the 2006–2007 flight of the balloon borne detector ANITA searching for radio pulses originating from neutrinos interacting in the Antarctic ice sheet, signals of air showers with frequencies up to 900 MHz were discovered serendipitously [20].

In addition, Gorham *et al.* [21] pointed out that the numerous, slow ionization electrons induced by the high-energy particles of the shower disk are expected to emit molecular bremsstrahlung at GHz frequencies. Several experiments were set up to search for such a signal using test beams [21–25] and air shower detectors [21,26–30].

The first unambiguous detections of microwave signals of air showers in the 3–4 GHz range were reported recently by two of these experiments, EASIER at the Pierre Auger Observatory [27] and CROME [30]. In this work we present the first study of the overall features of the microwave radiation of air showers using data from the CROME experiment. We show that the measured signal is compatible with the high-frequency tails of the geomagnetic and Askaryan (i.e., coherent radiation by the charge excess in the shower front) emission processes.

The CROME experiment.—The CROME experiment [29,30] was located within the KASCADE-Grande air shower array [31]. It consisted of various radio antennas covering a wide range of frequencies from about 1 MHz up to 12 GHz. The data reported in this Letter were taken with three C band (3.4–4.2 GHz) antennas, each consisting of a parabolic reflector with a diameter of 335 cm. The focal plane of each reflector was equipped with a 3×3 matrix of linearly polarized C band receivers. Hence, each antenna provided nine sharp, pencil-like beams with opening angles of $\lesssim 2°$ (half-power beamwidth) and about 41 dBi gain. In the course of the experiment, the four outermost beams of each antenna were upgraded with additional receivers for the measurement of two polarization directions.

The three C band antennas were pointed in different directions (15° from zenith towards magnetic south, zenith, and 15° from zenith towards magnetic north) to observe parts of the sky with varying angles relative to the local geomagnetic field (10°, 25°, and 40°, respectively). The pointing directions and radiation patterns of the antennas were validated using a calibrated airborne transmitter [29]. During the main operating period between May 2011 and November 2012, the experiment was gradually expanded to this final setup, with effective operating periods of 551 days for the vertical pointing, 378 days for the antenna pointed towards north, and 215 days for the antenna pointed towards south.

Logarithmic power detectors were used to measure the envelopes of the antenna signals within an effective bandwidth of about 600 MHz around 3.8 GHz. The response time of the complete system was about 3 ns, with a total system noise temperature of $\lesssim 90$ K.

The readout of all receivers was triggered by the detection of high-energy air showers with KASCADE-Grande, resulting in an effective energy range of 3×10^{15} to 10^{18} eV. The signals recorded within a window of $\pm 10\ \mu$s with respect to the KASCADE-Grande trigger were digitized and stored for offline analyses, together with the results of the standard shower reconstruction of KASCADE-Grande [31].

Event selection.—The common operating time of KASCADE-Grande and CROME amounts to about 10 000 hours, corresponding to about 19000 showers with energies $> 10^{16}$ eV having crossed the field of view of at least one receiver. Less than 1% of the events were discarded due to external interference or extreme weather conditions.

The expected arrival time of the microwave signal from each shower was calculated using the reconstructed shower geometry, accounting for the altitude-dependent refractive index and the measured signal propagation times in the detectors. The typical uncertainty of the expected signal arrival time is about 50 ns. For each trace, the signal strength within this time window is quantified relative to the average noise level outside of the window.

Selecting air showers with energies above 3×10^{16} eV and signal-to-noise ratios exceeding a threshold of 8 dB yields 37 event candidates with microwave signals. The expected number of noise signals exceeding the threshold level is estimated from data by repeating the analysis for shifted time windows, and it is found to be 9.4 ± 0.2.

The time traces of microwave signals of two air showers are shown in Fig. 1. The top panel shows the largest signal measured with CROME, 17.7 dB above the noise level. The energy of the shower was 2.5×10^{17} eV, the zenith angle 5.6°, and the core distance to the antenna 120 m. One of the two stereo events is shown in the bottom panel (shower energy 3.7×10^{16} eV, zenith angle 3.7°, core distance 110 m). The absolute timing of all detected pulses is well within the expected time window, and for the stereo events, the relative delays between the pulses are in good agreement with the expectations (cf. Fig. 1).

Properties of the microwave signal.—The reconstructed trajectory of each selected air shower typically intersects the fields of view of five receivers. Only the receivers viewing the air shower at high altitudes, usually above 2 km, detected a signal. Hence, the main emission region is close to the expected maximum of the shower development

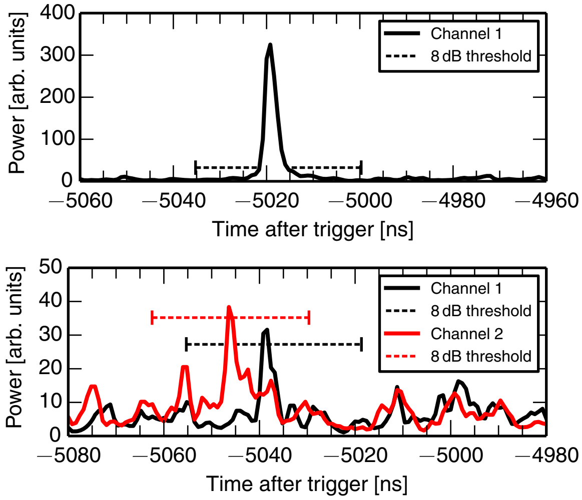

FIG. 1 (color online). Power (linear scale) as a function of time relative to the KASCADE-Grande trigger for the event with the highest signal-to-noise ratio (top panel) and a stereo event (bottom panel). The 8 dB thresholds for the signal search are shown as dashed lines, with the horizontal extents indicating the time windows in which signals are expected.

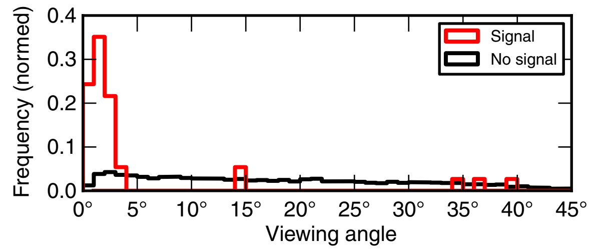

FIG. 2 (color online). Distribution of viewing angles for showers passing the KASCADE-Grande and geometry selection criteria for the 37 receivers with microwave signals above the search threshold (red line) and about 15000 receivers without (black line).

(about 4 km above ground for a vertical shower with an energy of 10^{17} eV).

In Fig. 2, the distribution of the viewing angles—the angles between the shower axes and the boresight axes of the receivers—is shown for events passing the shower selection criteria. The distribution of the events with a microwave signal is sharply peaked below 4° and thus differs significantly from that of the events without a signal. Hence, the majority of the showers were detected from their forward direction. Taking into account the fields of view of the receivers (about 2°) and the uncertainties of the shower geometry (about 1°), the angles of emission are compatible with the Cherenkov angle in air (about 1.1° at 4 km).

Further evidence for an emission in the forward direction is found in the distribution of the core positions of the detected showers: The core positions form a ring structure at a distance of 70–150 m around the antennas. This is compatible with the size of the Cherenkov cone projected on the ground from altitudes higher than 3 km.

Interpretation.—The observed radio signal of air showers in the MHz range stems mainly from two emission processes [32]. First, the deflection of the electrons and positrons of the shower disk in Earth's magnetic field results in time-varying transverse currents (geomagnetic radiation) [33,34]. Second, the shower disk contains 20%–30% more electrons than positrons, leading to a varying charge excess and, hence, electromagnetic radiation (Askaryan effect) [34–36]. Several simulation codes are available for describing these emission processes in detail. In the following, we will use CoREAS [10] to obtain predictions for the expected emission features in the GHz range [5,6,10,37].

The basic features of the expected microwave signal on the ground and the dependence on the longitudinal shower profile are illustrated in Fig. 3 for two vertical showers of 10^{17} eV simulated with CoREAS: A typical shower with a of maximum depth of $X_{\max} = 658\ \mathrm{g\,cm^{-2}}$ (upper panel) and a deep proton shower with $X_{\max} = 895\ \mathrm{g\,cm^{-2}}$ (lower panel).

To compare the measured events with the predicted radio signal, we first improve the purity of the event sample. By considering only events with a viewing angle less than 4° (cf. Fig. 2), we obtain 31 showers (including two stereo observations) for an expected number of 1.1 ± 0.1 noise signals. For these events, the positions at which the GHz signal is detected relative to the shower core are shown in Fig. 3. Both the structure of the Cherenkov-like ring and the asymmetries observed in data are qualitatively well reproduced by the typical shower.

Considering nearly vertical showers, the superposition of the mainly east-west polarized electric field of geomagnetic radiation and the radially inward-polarized field due to the Askaryan effect leads to a pronounced east-west asymmetry in the overall signal strength. With 14 and 3 events detected with the vertically pointing antenna east and west of the shower core, respectively, this asymmetry is visible in data. For the antenna oriented towards north, no significant east-west asymmetry is observed (4 vs 8 events), as can be expected for an increasing dominance of geomagnetic emission due to the larger geomagnetic angle.

Thus, the GHz observations are consistent with the known signatures of the radio emission of high-energy charged particles in an air shower which is collimated in a cone about the Cherenkov angle due to the refractive index of air, an effect first described by de Vries *et al.* [8]. An antenna located on or near this cone—projected from the main emission region near the shower maximum on the ground—receives a radio pulse of only a few ns duration. Hence, near the emission cone, a harder frequency spectrum and coherence up to GHz frequencies are expected.

A detailed comparison of the observed signal amplitudes with the CoREAS predictions can only be done after a full

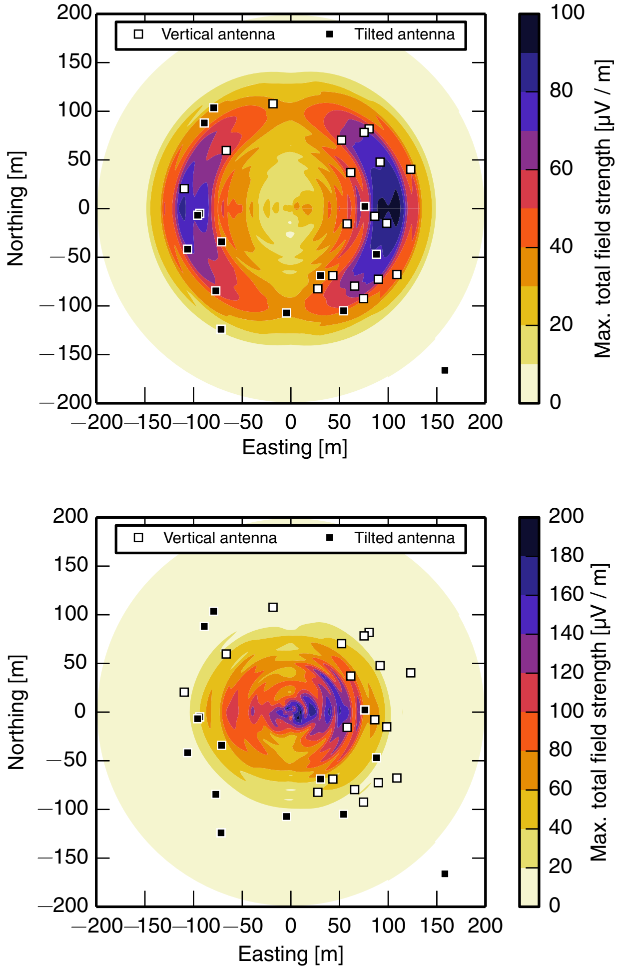

FIG. 3 (color online). Positions at which a microwave signal has been detected relative to the shower core at (0, 0). The color contours indicate the maximum total field strength at ground level predicted by CoREAS for a typical vertical ($X_{max} = 658\ \mathrm{g\,cm^{-2}}$, upper panel) and a very deep vertical shower ($X_{max} = 895\ \mathrm{g\,cm^{-2}}$, lower panel) of 10^{17} eV.

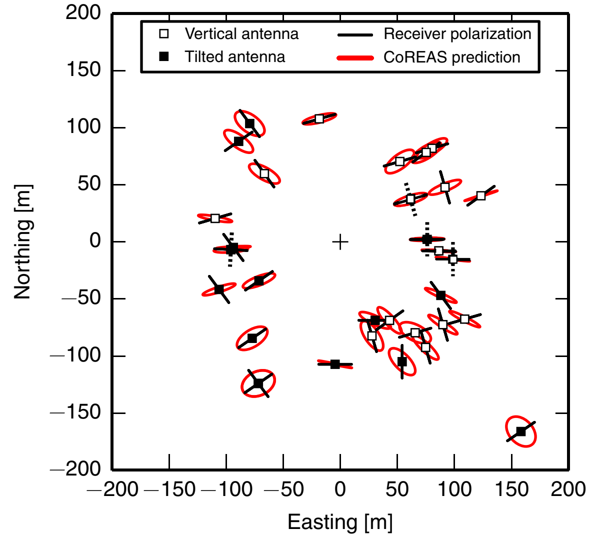

FIG. 4 (color online). Polarization directions of receivers in which a microwave signal was detected (black lines). In addition, the predicted polarization ellipses simulated with CoREAS for iron showers are shown in red. For dual-polarized receivers, the polarization direction in which no signal was detected is shown as a dashed line. The shower core is always at (0, 0).

end-to-end calibration of CROME and is beyond the scope of this article.

To compare the measured polarization directions with CoREAS predictions, we simulated showers for each observed event (cf. Fig. 4). Motivated by the composition measurement of KASCADE-Grande [38], iron nuclei were used. The polarization information can be compared directly for the three events detected with dual-polarized receivers. It is found that the signal was always detected only with the receiver whose polarization direction was close to that predicted in the simulations, but the statistics of such events is too small to draw conclusions.

Therefore, we applied a detector simulation to the time traces obtained from the CoREAS simulations and calculated the loss in detectable power due to the projection of the predicted electric field vector onto the polarization direction of the receivers (polarization loss). Assuming that the time-dependent local electric field vector is correctly described by the CoREAS predictions, we find an average polarization loss of 34% for the measured microwave signals. For unpolarized pulses from incoherent radiation with a flat frequency spectrum, an average polarization loss of $50.0\% \pm 3.5\%$ would be expected. Therefore, within this model, the hypothesis that the observed radio emission is unpolarized is rejected with a significance of 4.7σ.

The polarization pattern of the signal disfavors an explanation in terms of molecular bremsstrahlung as a dominant emission mechanism which is in qualitative agreement with recent findings [22,23,25].

Conclusions and outlook.—Using air showers measured with CROME in coincidence with KASCADE-Grande, we have determined fundamental properties of the microwave emission of air showers in the forward direction. We have shown that the spatial and angular distributions of the microwave signal are in good agreement with the extension of the well-known radio emission processes at tens of MHz into the GHz range close to the Cherenkov angle [5,8,10]. The collected polarization information strongly supports this conclusion.

We have illustrated that this technique can be successfully used for the measurement of extensive air showers. The main advantages for the observation in the GHz range are the low background noise, the nearly perfect transparency of the atmosphere at microwave frequencies, and the availability of a well-developed technology for microwave detection [21].

One can envisage various applications of measuring air showers with setups similar to the one presented in this Letter. For example, the data collected by the balloon-borne

ANITA detector at the South Pole [20] or future balloon or satellite experiments of this type [39,40] could be experimentally verified and calibrated.

Additionally, in contrast to optical detectors such as imaging atmospheric Cherenkov telescopes [41], the possibility of measuring with a nearly 100% duty cycle and using simple metallic reflectors instead of optical mirrors could make this measurement technique promising for air showers with energies above hundreds of TeV. Particularly, a measurement of inclined air showers, where the footprint of the microwave signal extends over hundreds of meters, could compete with optical detectors.

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