Possibility of studying cosmic rays with energies > 10^{20} eV

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(Submitted 10 August 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 6, 216–219 (20 September 1982)

It may be possible to detect extensive air showers at energies above 10^{20} eV on the basis of their radio emission, with the radio waves reflected and scattered from the ionosphere. Estimates show that it would be possible to move up to energies of 10^{22} eV in research on the spectrum of cosmic rays, with statistics on the order of one event per year in the absence of a "relict cutoff" of the spectrum of cosmic protons or in the case of oblique extensive air showers produced by neutrinos.

PACS numbers: 94.40.Lx, 94.40.Pa

Whether there is an upper limit on the masses of elementary particles is a question of fundamental interest,[1] warranting special experiments.

If the ultra massive particles ($M \sim 10^{23}$–10^{25} eV) predicted by grand unified theories (leptoquarks, monopoles, etc.) do in fact exist, then their interactions may give rise to hadrons and leptons with energies well above 10^{20} eV. If a maximon exists (a stable elementary black hole with a mass $\sim 10^{-5}$ g), the spectrum of elementary particles (including neutrinos) which arise in the final stage of evolution of systems of several maximons could extend up to energies of 10^{28} eV (Refs. 1 and 2). Searches for particles with energies of 10^{20}–10^{28} eV could be carried out in experiments of the DUMAND type and through the detection of superhigh-energy extensive air showers in the atmosphere by radio methods.[1,2]

Research on extensive air showers near 10^{20} eV will also make it possible to determine whether the spectrum of cosmic-ray protons is cut off by relict photons. If the spectra of protons with $E_p > 10^{20}$ eV are suppressed there remains the possibility of detecting cascades produced by neutrinos with energies $E_\nu > 10^{20}$ eV (provided, of course, that significant fluxes of such neutrinos exist) both in DUMAND experiments and in the atmosphere. The length of electron–photon cascades in water (or in soil) at $E_0 > 10^{20}$ eV is more than several hundred meters, so it is worthwhile to examine the possibility of detecting cascades which might be caused by neutrions with $E_\nu > 10^{20}$ eV near the earth's surface in soil (or water) and whose development might continue upward into the atmosphere.

The possibility of detecting extensive air showers on the basis of their coherent radio emission was first pointed out by Askar'yan.[3] Radio emission is caused by the following mechanisms: Čerenkov dipole emission, synchrotron radiation in the geomagnetic field, relativistic bremsstrahlung in the geoelectric field, transition radiation when an extensive air shower "collides" with the earth, and the radiation due to the effective stopping of the charge of an extensive air shower because of its "aging." The first observations[4] showed that the detection threshold is at 10^{15}–10^{16} eV. Since the effective charge of a cascade is proportional to the primary energy (the number of particles in the cascade is $\sim E_0$, and $q \sim E_0$), the power level of the coherent radio emission increases with the energy in proportion to E_0^2. A search for the radio emission of extensive air showers would thus be the most appropriate method for detecting superhigh-energy showers.[2] It is improbable, however, that the direct radio emission will be detected at $E_0 > 10^{20}$ eV, since the emission is highly directional, and the statistics are very poor. In this paper we will discuss the possibility of detecting the radio emission of extensive air showers with energies $> 10^{20}$ eV which is scattered upon reflection from the earth and the ionosphere.

We know that one extensive air shower with an energy $E_0 \sim 10^{19}$ eV is incident on an area of 1 km^2 in 1 sr per year. If the integrated spectrum is E_0^{-2}, we will have to increase the effective detection area by four to six orders of magnitude in order to move up to energies 10^{21}–10^{22} eV. Since the emission mechanisms are highly directional (except the norelativistic dipole emission), the "illuminated" area on the earth is small (with a diameter on the order of hundreds of meters); consequently, increasing the number of detectors would not be an effective way to move to higher energies.

We wish to point out that after reflection from the earth and then from the ionspheric F layer, at a height of 300–350 km (or from the sporadic E layer), with strong scatter over an angular interval up to 20°, which is characteristic of low and high latitudes,[5] the illuminated area would increase sharply.[1)] Let us estimate the strength of a radio signal from an extensive air shower at frequencies $f \cong 25$–45 MHz in a band $\Delta F \sim 5$ MHz at energies $E \cong 10^{21}$ eV. We assume that a receiving antenna with a directional pattern about 20° in size is installed at some point and oriented at an angle of about 30° with the horizontal. This antenna would monitor an elliptical area with dimensions of 300×600 km in the ionosphere, on which a signal from an extensive air shower would be incident in a solid angle of 0.05 sr from a region of the same dimensions. Because of the ionospheric scatter, the spot illuminated by an extensive air shower would also have dimensions of 300×600 km (Fig. 1).

The experimental value of the electric field in a 5-MHz band is about 20μV/m (at a noise level of 10μV/m) at a distance of about 300 m from the axis of an extensive air shower with $E_0 = 10^{17}$ eV. At $E_0 = 10^{21}$ eV we can expect a signal at the level of 0.3 V/m at the point of incidence of the shower; with an average absorption in the ionospher on the orde of 10 dB and with a maximum loss upon reflection from dry soil on the order of 8 dB, the signal near the antenna would be about 30 μV/m, i.e., three times the noise level. An observation area $\sim 10^5$ km^2 would (with allowance for the solid angle) provide statistics on the order of one event per year. From the theory for radio emission and with information on the state of the ionosphere and the soil (the reflection height, the degree of scatter, and the absorption level) we could hope for an accuracy at the level of 50% in the determination of the shower energy. By choosing

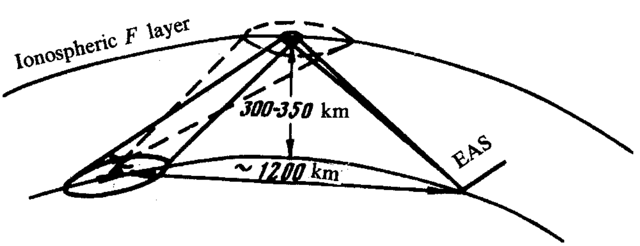

FIG. 1.

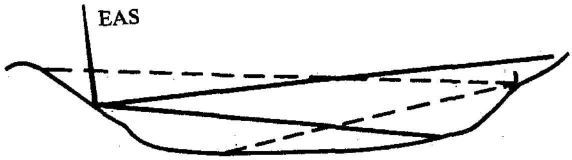

FIG. 2.

nearly vertical reception angles and reflection from sporadic E layers (heights of 100–120 km) we could detect extensive air showers with $E_0 = 10^{20}$ eV. Finally, by using the reflection and scatter from one slope of a mountain valley, on the order of 30 km wide, we could detect showers with an energy on the order of 3×10^{19} eV. Since there is no ionospheric absorption, we could reduce the loss in the soil and achieve a strong scatter, i.e., improve the statistics, by specially preparing the region in which the showe is incident (Fig. 2).

In the proposed experiments it is necessary to resolve the complicated problem of distinguishing the infrequent pulsed signals against the background of natural and industrial noise. The successful resolution of this problem requires knowledge of the pulse characteristics: the spectrum of the signal, its duration, and the size of its front (on the order of 100 km). The limited size of the front of the useful signal would make it a simple matter to distinguish all distant discharges in electrical storms. Furthermore, by using auxiliary channels with omnidirectional antennas, local noise could be distinguished. There is also the question of how to distinguish between the signal from remote extensive air showers and the signals from lower-energy showers which are directed right at the antenna aperture. It should be taken into account here that the duration of a signal scattered from the ionosphere or from the surface of the soil is substantially increased, so that the scattered signal could be reliably distinguished from a direct signal. Finally, strong signals from radio stations, radar stations, etc., can be eliminated with rejection filters.

If the cosmic-ray spectrum at $E > 10^{20}$ eV falls off more slowly than E^{-2}, we could use the method described above to detect the radio emission from extensive air showers with energies above 10^{22} eV.

We are deeply indebted to G. A. Askar'yan, G. T. Zatsepin, V. V. Migulin, and G. B. Khristiansen for useful discussions.

[1)] G. A. Askar'yan has pointed out to us that at large values of E_0 the multiple scattering of shower particles would also tend to increase the size of the spot on the earth slightly.

[1] M. A. Markov, "On the upper limit of the cosmic ray energy spectrum (DUMAND-type experiment)," Preprint INR, 1981, *P*-0197, Moscow; M. A. Markov, "On the maximon and the concept of elementary particles," Preprint INR, 1981, *P*-0206, Moscow; M. A. Markov and I. M. Zheleznykh, Proceedings of the 1979 DUMAND Workshops at Khabarovsk and Lake Baikal (ed. J. Learned), Honolulu, p. 177.

[2] L. G. Dedenko, M. A. Markov, B. E. Stern, and I. M. Zheleznykh, Proceedings of the 17th International Cosmic Ray Conference, Paris, 1981, Vol. 10, p. 303; L. G. Dedenko, N. A. Markov, and I. M. Zheleznykh, Proceedings of Neutrino–81, Maui, Hawaii, Vol. 1, p. 292.

[3] G. A. Askar'yan, Zh. Eksp. Teor. Fiz. **41**, 616 (1961) [Sov. Phys. JETP **14**, 441 (1962)].

[4] J. V. Jelly *et al.*, Nature **205**, 327 (1965); I. A. Borzhkovskiĭ, V. D. Volovik, and E. S. Shatko, Izv. Akad. Nauk SSSR. Ser. Fiz. **30**, 1705 (1966).

[5] B. N. Gershman, Dinamika ionosfernoĭ plazmy (Dynamics of the Ionospheric Plasma), Nauka, 1974.

[6]G. B. Khristiansen, G. V. Kulikov, and T. A. Fomin, Kosmicheskoe izluchenie sverkhvysokikh energiĭ (Ultrahigh-energy cosmic radiation), Atomizdat, Moscow, 1975.

Translated by Dave Parsons
Edited by S. J. Amoretty