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Coherent Cherenkov radio emission and problems of ultrahigh-energy cosmic ray and neutrino detection

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Abstract

This review is concerned with prospects for employment of coherent Cherenkov radio emission for detecting ultrahigh-energy cosmic rays and neutrinos. Reasons for interest in and problems of studying the ultrahigh-energy particles are summarized. A history of the development of a radio-wave method and its main merits are recalled. Current experiments and proposals based on this method are briefly discussed with emphasize on the most recent Lunar Orbital Radio Detector (LORD) proposal.

Keywords: Ultrahigh-energy particles; Cosmic rays; Neutrino; Radio-wave emission; Cascades

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1. Introduction

I was lucky to work under the direction of P.A. Cherenkov for about 20 years and now I am very happy to have a talk at the Conference dedicated to his memory. It is remarkable that, with the passage of years, Cherenkov's results not only retained their actuality but increased their significance.

For the majority of physicists, Cherenkov radiation is traditionally associated with radiation in *optical range*, where it was discovered by Cherenkov and where it found very wide applications in particle and cosmic ray (CR) physics. In this respect, my talk has, so to speak, non-traditional orientation. I will discuss employment of Cherenkov emission in *radio-frequency band*. Currently, great interest is being shown in this field. The reason is that it is the Cherenkov radio emission with which the main hopes for a progress in ultrahigh-energy cosmic ray and neutrino studies are associated.

Incidentally, this year we have another jubilee relevant both to P.A. Cherenkov and CRs. The point is that 70 years ago, in 1934, a group of young physicists from Lebedev Physical Institute, consisting of P.A. Cherenkov, N.A. Dobrotin, and I.M. Frank, was sent to Elbrus, where they studied atmospheric showers discovered previously by D.V. Skobeltsyn at sea level. That was the first mountain CR experiment in our country.

2. Ultrahigh-energy cosmic rays and neutrinos

One of the most intriguing problems of astroparticle physics is the question what the highest particle energies are in nature and what their sources are (Markov, 1960; Berezinsky, 2003). For answering this question, over many decades elapsed after the CR discovery, bigger and bigger detectors were constructed to detect higher- and higher-energy and, consequently, rarer and rarer CR events. To date, at the biggest CR arrays, about two tens of events with macroscopic energies $\geqslant 10^{20}\,\text{eV} \approx 16\,\text{J}$ have been detected. These are the so-called ultrahigh-energy CRs (UHECR). We know neither their nature, nor their sources or processes where they were accelerated to such extremely high energies. Moreover,

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according to our current understanding of the Universe, these particles should not exist (more precisely—should not be observed in the vicinity of the Solar system) owing to the Greisen–Zatsepin–Kuzmin CR spectrum cutoff (Zatsepin and Kuzmin, 1966; Greisen, 1966) caused by interaction with the microwave cosmic background. However, such particles do exist. By now, the highest detected energy is 3×10^{20} eV. There are no reasons to believe that, at this energy, we reached a limit in the CR source spectra set by nature. In fact, we do not know any clear constraints on the CR spectrum endpoint until the GUT scale ($\sim10^{24}$ eV). More likely, this maximum detected energy is a temporal limitation set by the scales of existing arrays ($\leqslant 100\,\mathrm{km}^2$), since the CR flux sharply decreases with increasing energy and amounts about one particle per km^2 per century at $E\geqslant10^{20}$ eV.

The situation with the UHECR became even more complicated recently, after publication of some preliminary data from the HiRes collaboration (Abu-Zayyad et al., 2005) which are inconsistent with the previous data. In any case, more data on the UHECR are urgently needed. Interest to these particles is very high because it is expected that a clarification of the UHECR nature could result in fascinating physical and astrophysical findings and, quite possibly, in a radically new physics. In the event that macroscopic astrophysical objects are the sources of the UHECR, studies of these particles allow better understanding of acceleration mechanisms in superpower accelerators of the Universe. At the same time, the energy region under consideration is beyond a reach of terrestrial accelerators and thus investigation of the UHECR offers a unique opportunity for studying particle physics at such a ultrahigh-energy scale.

Detection of ultrahigh-energy neutrinos (UHEN) is also of great importance for astrophysics. Even at energies close to the Grand Unification scale, the Universe is appreciably transparent for neutrinos. Therefore, these particles can come from very remote sources and consequently could be a very efficient instrument of high-energy astrophysics. Measurements of UHEN spectra are important for determining limiting energies both in acceleration in superpower astrophysical accelerators and in decays of hypothetical superheavy particles.

The main problem of both UHECR and UHEN event detection is their rarity. As an example, it can be estimated that, for the minimum expected (GZK-) neutrino flux, we may find only 1 event every two years in a 1 km^3 detector. It means that detectors with huge apertures ($S\geqslant10^5\,\mathrm{km}^2$ for CR and $V\geqslant100\,\mathrm{km}^3$ for neutrinos) are required for collecting a statistically significant amount of events at ultrahigh energies. Traditional methods become inadequate for constructing such detectors and new efficient methods are needed. In recent years, it becomes more and more apparent that the most promising method for both UHECR and UHEN detection is the coherent Cherenkov radiation method originally proposed in the Lebedev Physical Institute.

3. A little bit of history

It is well known that optical Cherenkov radiation from extensive air showers (EAS) was observed for the first time by Jelley in 1953 (Jelley, 1958). Since then the Cherenkov method became one of the most efficient experimental methods in CR physics. At about the same time, an appealing idea of extending the Cherenkov method to the radio frequency band (which is free of a number of constraints inherent to optical measurements) was discussed. However, the following considerations led to a pessimistic assessment of this possibility. Firstly, the Cherenkov radiation spectrum is proportional to the frequency f. When passing from optical to the radio-frequency range, f decreases by some 5–8 orders of magnitude, and so does the signal. Secondly, in the radio-frequency band, when the radiation wavelength becomes longer than the spacing between individual particles in the shower, destructive interference should result in a cancellation of radiation from positive and negative charged shower particles. At that time, the shower was believed to be electrically neutral. Therefore, the absence of radiation at wavelengths longer than a few centimeters was expected.

An important step was made by G.A. Askaryan from Lebedev Physical Institute in 1961 (Askaryan, 1961). Askaryan pointed out that the interaction of shower particles with atomic electrons ($\gamma+e^-_{\mathrm{atom}}\to\gamma+e^-$, $e^++e^-_{\mathrm{atom}}\to e^++e^-$, $e^-+e^-_{\mathrm{atom}}\to e^-+e^-$) should result in drawing electrons off the surrounding medium and transferring them into the shower disk. In addition, shower positrons should annihilate in flight ($e^++e^-_{\mathrm{atom}}\to\gamma+\gamma$). The combination of these processes gives rise to the shower charge asymmetry, i.e., to an excess of negative charged particles in the shower disk which may be as much as 30% of the total number of shower particles. These fast excess electrons can emit radio waves through the Cherenkov mechanism. Askaryan also pointed out some appropriate media which are highly transparent for radio waves and are abundant in nature. These media are ice, rock salt, lunar regolith, and, of course, the atmosphere.

An essential aspect of Cherenkov radio emission from cascades is coherence. When the wavelength is larger than the characteristic shower size, the radiation is coherent, and the radiated electric field is proportional to the number of excess electrons, N_{ex}. On the other hand, this number is proportional to the shower energy, $N_{\mathrm{ex}}\sim E_{\mathrm{sh}}$. This means that the power of the coherent