Neutrino and muon detection from the radio-emission of cascades created by them in natural dielectric media

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The possibility of constructing a radiodetector for muons and neutrinos with a volume of 10^9–10^{11} m^3 in glacial and polar ice masses with low absorption of decimeter radio waves (4–12 dB/km) is demonstrated. A number of problems in neutrino astrophysics, neutrino physics, the physics of high-energy muons, and others, which can be solved with the help of the proposed detector, are indicated.

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The study of interactions of elementary particles in cosmic rays at energies that are not accessible to accelerators, problems in high and ultrahigh energy neutrino astrophysics, and the search for new phenomena and particles predicted by the "grand unification" theories and supersymmetry require the creation of ground-based, underground and deep underwater detectors with large areas and volumes. Thus the possibilities of deep underwater detection of neutrinos[1] in devices with a volume to 10^7 m^3 and more in the optical and acoustical variants (project DUMAND[2]) are being actively discussed and investigated. M. A. Markov also proposed to investigate the possibility of detecting neutrinos in the ice in Antarctica, in particular, using an acoustical method.

The method of recording cascades in dense media (in layers of ice, permafrost, very dry rocks) according to the radio emission of the excess charge, proposed by Askar'yan,[3] is in our opinion a promising method for recording interactions of elementary particles in very large volumes of matter. The dimensions of the cascades in the dense substance are such that coherent emission of excess charge in the cascade is possible (the intensity of the radiation is proportional to the square of the cascade energy) at decimeter wavelengths. For this reason, it was proposed in Ref. 4 that a system of dielectric (polyethylene) strips, each of which plays the role of a wave guide for radio waves in this region, be used as a detector of electron-photon or hadronic cascades from muons in a volume of water $\sim 10^5$ m^3.

We shall examine below the possibility of building radio detectors for muons and neutrinos with 10^9–10^{11} m^3 of glacial or polar ice (in Antarctica, Greenland, etc.) with a relatively small number of detecting elements (antennas) placed on the surface of the ice. The proposal is based on the fact that the absorption of radio waves in ice at frequencies in the range 10^7–3×10^9 Hz turns out to be very low[5,6] (at a temperature of $-50\,^\circ$C at frequencies 500–1000 MHz, it amounts to $(4$–$12)\times10^{-3}$ dB/m), which permits receiving weak radio signals from distances of the order of 1 km, and the direction and energy of the cascade can be determined from the shape and dimensions of the region of reception of the Vavilov-Čerenkov radio emission, entering from the lower hemisphere (intersection of the Čerenkov cone with an angle of 56° with the surface of the ice). We note that scattering of radio waves by small inhomogeneities in the ice is negligible at frequencies lower than 1 GHz.[7] Other natural dielectrics, for example, dry sand, can be considered for the detecting medium, but absorption of radio waves in them is much higher; 0.05 dB/m at a frequency of 30 MHz[7]. The possibility of recording electronic neutrinos in layers of salt was examined in Ref. 8.

According to Ref. 3, the excess charge q amounts to 10% of the total number of electrons and positrons in the cascade, so that $q = e\cdot 5\times10^{-10}\,E_0$ (eV) (E_0 is the energy of the cascade). The energy of the Valilov-Čerenkov radiation in the frequency band $\Delta\omega$ accompanying the passage of an excess charge q at a distance l is given by the well-known equation

$$W = \frac{q^2}{c^2}\,\omega\Delta\omega l\,(1 - 1/\beta^2 n^2), \tag{1}$$

where n is the index of refraction of ice, and $n^2 = 3\times17^5$. Setting $\Delta\omega = \omega\times10^{-1}$, $\omega = 2\pi f$, $f = 10^9$ Hz, $l = 200$ cm (l is the effective length of the cascade), for energies in the range $E_0 = 10^{13}$–10^{16} eV we obtain $W = 3\times(10^{-10}$–$10^{-4})$. This energy arrives in a ring-shaped region with area depending on the depth H, at which the cascade from the neutrino is formed. In the case of vertical orientation of the cascade axes, $S = 2\pi H^2\Delta\alpha\sqrt{\epsilon - 1}/\epsilon \simeq 0.3\,H^2$ (if the expansion of the Čerenkov cone is $\Delta\alpha \sim 5°$), so that the energy of the radio pulse per 1 m^2 is $W/S = 3W/H^2$. The energy of the noise during the action of the useful signal $\sim 1/\Delta f$ is 10^{-13} erg, so that after taking into account the noise in the antenna, the receiver, the atmosphere, and the ice, the effective noise temperature, according to Ref. 6, is $\sim 1000°$. Therefore, at a cascade-formation depth of $H = 100$ m, we shall choose the threshold energy of the cascade to be $E_0 \simeq 3\times10^{13}$ eV and at a depth of 1 km $\sim 5\times10^{14}$ eV (the signal-to-noise ratio is 10 with an effective antenna area of ~ 1 m^2).

If antennas (with low noise preamplifiers) with an effective area of the order of several square meters and a band exceeding 100 MHz at a frequency of the order of 1 GHz are placed on an area of 3×3 km on the surface of ice every 100–200 m (see Fig. 1), then the effective volume of the detector with an ice depth of 1 km will be $\sim 10^{10}$ m^3. The radio signal from the cascade initiated by a neutrino arriving from the bottom toward the top at a depth of 1 km, taking into account the spreading of the Čerenkov cone, will be received in several tens of receivers situated in the region between two ellipses or in the region between two parabolas, when the cascade from muons and the neutrino arrive from the side. The orientation of the cascade (the angle θ with the

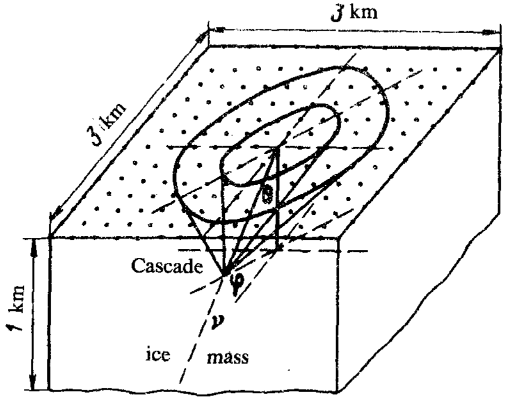

FIG. 1.

vertical and the azimuth φ, see Fig. 1) and the distance from it (therefore, it is possible to find the energy of the cascade) can be determined from the shape, orientation, and size of the illuminated region. We emphasize that the detection of a signal with a large number of receivers (multiple coincidences) will decrease the detection threshold even in the presence of sporadic noise in ice. The detect cascades with lower energy ($\lesssim 10^{13}$ eV), formed at small depths of the order of tens of meters, it is proposed that one of the 200×200-meter cells be filled with a dense grid of antennas, for example, every 20 meters, i.e., an additional ~ 100 antennas be added. It can also be shown that noise arising from the cascades initiated by cosmic-ray hadrons are easily identified by the shape of the illuminated region.

With the help of the proposed radio detector of muons and neutrinos (RAMIND), it is possible to search for local sources of high-energy neutrinos of galactic and extragalactic origin, to study absorption of neutrinos with $E > 10^{13}$ eV in the earth, and to generate "direct" neutrinos.[13] There is special interest in investigating the reaction $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hardrons in the regions of the W boson resonance.[9–11] The recently discovered W boson has a mass of ~ 80 GeV and, therefore, a resonance energy of $E_{\rm res} = M_W^2/2m_e = 6 \times 10^6$ GeV. In $\sim 10^{11}$ m^3 of ice, several tens of hadrons cascades with energies $\sim 6 \times 10^6$ GeV can be expected in a year.[10]

By studying the spectrum of cascades initiated in the detector by muons from horizontal extensive atmospheric showers, it is possible to determine the spectrum of such muons and, for example, to obtain information of the chemical composition of the primary cosmic radiation.

The proposed detector is an adequate detector for searching for supersymmetrical high-energy particles (photino) and neutrinos (and other elementary particles) at superhigh energies ($E > 10^{20}$ eV). For example if maximons with mass $\sim 10^{-5}$ g exist, then for certain scenarios of the universe, the upper boundary of the energy spectrum of the neutrino could be $\sim 10^{28}$ eV.[12] If significant fluxes of neutrinos with $E > 10^{20}$ eV exist, then such neutrinos could give rise to nearly horizontal cascades in soil.

The neutrino radio detector can be used in geophysical experiments in which high-energy neutrino beams from accelerators are "transmitted" through the earth.

In conclusion, we emphasize that the proposed radio detector for muons and neutrions, in spite of its simplicity and low cost, will increase the volume of events recorded by 5–7 orders of magnitude compared with the volume of existing devices, which will give new possibilities for solving fundamental problems in high-energy physics and astrophysics.

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