Radio-frequency emission and currents from showers and muons produced in a medium by a beam of high-energy neutrinos

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The current produced by muons and showers in a beam of high-energy neutrinos is analyzed. This current is calculated, as is the electromagnetic field which arises during its flow and modulation. A deep underground source of electromagnetic fields could be developed for use in detecting the neutrino beam and for rf subsurface imaging of rock formations.

The use of high-energy neutrino beams has recently attracted considerable interest for geophysical research and for exploring for mineral deposits (see Ref. 1, for example). The use of such beams is becoming feasible, since the accelerators of the next generation may be able to produce pulses of $N_\nu \simeq 3 \times 10^{13}$ muon neutrinos per accelerator pulse with neutrino energies $\mathscr{E}_\nu \sim 1$ TeV (10^{12} eV) with a small angular divergence $\theta \sim 10^{-5}$ (corresponding to a beam 10 m in radius at a distance of 10^3 km).

As they interact with nuclei, such neutrinos generate hadron-electron-electromagnetic showers and high-energy muons with $\mathscr{E}_\mu \cong 1$ TeV, and these showers have been suggested for use in geophysical research. The idea is to make use of the generation of sound[2–4] as the particle beams lose energy to determine the sound velocity and other properties of rock formations; to use the absorption and scattering of muons to determine the properties of rock formations below the earth's surface; etc.

In this letter we analyze the currents and rf emission from showers and muons produced by neutrino beams and the possibility of using them to detect neutrino beams, for rf subsurface imaging, and for studying the properties and distributions of rock formations in the interior of the earth.

1. MUON CHARGES AND CURRENTS IN NEUTRINO BEAMS

Because of the particular pion focusing conditions, the pions in the decay channel ordinarily have a charge of a definite sign. Their decay thus gives rise to either muon neutrinos (from π_+) or muon antineutrinos (from π_-). Such neutrino beams produce muon beams of a definite charge, μ_- from neutrinos and μ_+ from antineutrinos:

$$\nu + p \to \mu_- + \ldots; \quad (\sigma_{\nu p \mu_-} \simeq 0{,}17 \text{ arb. units}); \quad \nu + n \to \mu_- + \ldots;$$

$$(\sigma_{\nu n \mu_-} \simeq 0{,}3); \quad \tilde{\nu} + p \to \mu_+ + \ldots; \ (\sigma_{\nu p \mu_+} \simeq 0{,}13); \quad \tilde{\nu} + n \to \mu_+ + \ldots;$$

($\sigma_{\nu n \mu_+} \simeq 0.09$). Even in a beam which is a mixture of ν and $\tilde{\nu}$, we might note, an excess of muons of one charge or the other forms because of the difference between the muon production cross sections, $\sigma_{\nu\mu_-} \simeq 2\sigma_{\bar{\nu}\mu_+}$, on the average per nucleon (see Ref. 6, for example).

If the neutrino flux density $\dot{N}_\nu$ is given ($\sim N_\nu/T$, where T is the time required for the dumping of the beam from the accelerator; this time can be varied over a broad range), then the quasiequilibrium current produced by the muons is $J_\mu \simeq e\dot{N}_\nu L_\mu/L_\nu$, where L_μ is the range of the muons ($L_\mu \simeq 1$ km), and L_ν is the range of the neutrinos (at the energies of interest here, $L_\nu \simeq 3\times 10^4$ km).

The moving meson bunch $Q_\mu \simeq eN_\nu(L_\mu/L_\nu) \simeq 3\times 10^{-5}\, eN_\nu$ contains many particles and produces intense coherent emission at wavelengths larger than the dimensions of the bunch, $l \sim cT$. For example, for $T \simeq 10^{-6}$ s, $N_\nu \simeq 3\times 10^{13}$, and $L_\mu/L_\nu \simeq 3\times 10^{-5}$, we find $J_\mu \simeq 0.3$ mA and $N_\mu \simeq \frac{1}{e} Q_\mu \simeq 3\times 10^{-5} N_\nu \simeq 10^9$.

2. MOTION OF THE NET CHARGE OF SHOWERS IN A NEUTRINO BEAM

Since δ-electrons and Compton-effect electrons are caught up in the shower, each shower produces a net moving negative charge,[7,8] $n_{\text{net}} \simeq 0.2 n_c \simeq 0.2(\mathscr{E}_\nu/10^2\ \text{MeV}) \simeq 0.2\times 10^4$ charges. The average net charge is $N_{\text{net}} \sim n_{\text{net}} L_c N_\nu/L_\nu$, where L_c is the length of the cascade ($L_c \lesssim 5$ m). Let us compare the net charges: $N_e/N_\mu \simeq n_{e\,\text{net}} \times L_c/L_\mu \simeq n_{\text{net}}\ 5\times 10^{-3} \simeq 10$. In other words, the net charge of the showers can exceed the muon charge.

3. RADIATION FROM THE MOTION OF CHARGES

The motion of a charge can cause a burst of rf emission. If this emission occurs in rock formations with good dielectric properties, i.e., $\epsilon \simeq 10$ (and a low conductivity $\sigma \simeq 10^7$–10^6 abs), the return current cannot significantly weaken the directed motion of the charge (the cancellation time is $\tau \sim \epsilon/2\pi\sigma$), and Čerenkov or transition radiation should arise as a result of the motion of the charge faster than the speed of light.

Using the expression for the energy loss per unit length in the case of Čerenkov radiation,

$$\mathscr{E}_1 \simeq \frac{Q^2}{c^2} \int \omega \left[1 - \frac{1}{\beta^2 n^2(\omega)}\right] d\omega \sim \frac{Q^2}{c^2}\, \omega\Delta\omega,$$

we can estimate a lower limit on the radiation power:

$$W \sim \mathscr{E}_1 c \simeq N^2 e^2 \omega\,\Delta\omega/c \simeq (2\pi)^2 N^2 e^2/cT^2$$

for $N \sim 10^{10}$; with $T \sim 1\ \mu$s we find $W \simeq 3$ mW. This is a lower limit for a very diffuse radiation cone (in the case of a sharp cone, the radiation field is far more intense at the front of the cone in an angle $\varphi \sim \arccos 1/n$).The large dimensions which the bunch may have (acccording to the coherence condition $\lambda' = \lambda/n > l_\parallel$ and $l_\perp$, for frequencies below 1 MHz we would have $l \lesssim 10^2$ m) and the high power of the pulse make it possible to use neutrino beams of large diameters and accelerators of lower energies.

These estimates show that it is possible to produce an rf source deep underground and to use the distortions in the emission from this source to detect zones of elevated conductivity or elevated absorption (oil-bearing or water-bearing strata, metallic ores, etc.).

We might note that the rf subsurface imaging of rock formations[9] is carried out in

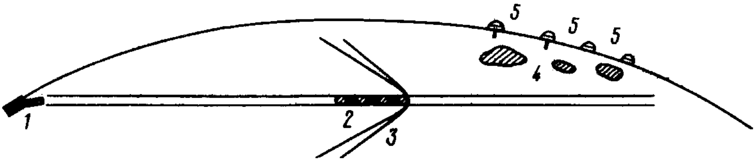

FIG. 1. Emission of electromagnetic waves from a moving charge formation produced by a neutrino beam. 1—The accelerator which is the source of the neutrino beam; 2—the formation of moving charge produced by the neutrino beam; 3—cone of Čerenkov electromagnetic radiation; 4—inhomogeneities in the rock; 5—detectors which measure the electromagnetic field.

the frequency range 10^4–10^6 Hz. The repetition and modulation of the pulses facilitates their reception and their discrimination from noise. It is also possible to use other, more intense ($N_\nu \sim 10^{18}$), transportable sources of neutrinos (see Ref. 5, for example) with a lower energy and directionality ($\theta \lesssim 0.3$) over shorter distances.

4. INHOMOGENEITIES OF THE CURRENTS AND THE ELECTRIC FIELD

The appearance of a current J_μ and of a current from the net charge of cascades, J_c, can give rise to electric charge in the case of a longitudinal inhomogeneity of the currents, $(\partial J/\partial z) = \dot{Q}_1 + (2\pi\sigma/\epsilon)Q_1$, where Q_1 is the charge per unit length. For good dielectrics ($T\sigma < 1$) the charge Q_1 produces at a distance $R \lesssim l$ a field $E \sim 2Q_1/R$. If the dimension of the inhomogeneity of the current satisfies $l < 1$ km, we would have $E \simeq (2eN_\nu/lR)(L_\mu/L_\nu) \simeq 1$ μV/cm, from the muon current alone.

We see from this discussion that the electromagnetic fields which arise from a neutrino beam are completely detectable and can be exploited to detect and study rock distributions. The properties and dimensions of an inhomogeneity can be determined from the change in the distribution of the signal and from the change in its delay (upon the displacement of the beam when it strikes an inhomogeneity).

The rf method proposed in Refs. 7 and 8 for detecting widely spaced particles in large volumes of natural media with a low rf absorption has recently been proposed again.[10]

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[1] A. De Rujula, S. L. Glashow, R. Wilson, and G. Charpak, Preprint CERN (Switzerland), Harvard (USA), 1983.

[2] G. A. Askar'yan, At. Energ. **3**, 152 (1957).

[3] G. A. Askar'yan and B. A. Dolgoshein, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 232 (1977) [JETP Lett. **25**, 213 (1977)].

[4] G. A. Askar'yan, B. A. Dolgoshein, A. N. Kalinovsky, and A. V. Mokhov, Nucl. Instrum. Methods **164**, 267 (1979).

[5] G. A. Askar'yan, Usp. Fiz. Nauk **128**, 727 (1974) (*sic*); Pis'ma Zh. Eksp. Teor. Fiz. **28**, 322 (1978) [JETP Lett. **28**, 296 (1978)].

[6] L. B. Okun', Leptony i kvarki (Leptons and Quarks), Nauka, Moscow, 1981, p. 142.

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

[8] G. A. Askar'yan, Zh. Eksp. Teor. Fiz. **48**, 988 (1965) [Sov. Phys. JETP **21**, 658 (1965)].
[9] V. V. Rzhevskiĭ and E. B. Korenberg, Rudnichnaya radiointroskopiya i radiosvyaz' (Radio-Frequency Subsurface Imaging and Communications for Mining Applications), Nedra, Moscow, 1978.
[10] G. A. Gusev and I. M. Zheleznykh, Pis'ma Zh. Eksp. Teor. Fiz. **38**, 505 (1983) [JETP Lett. **38**, 611 (1983)].

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