Investigation of the Earth by means of neutrinos. Neutrino geology

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Possible applications are described for high energy neutrino beams in the production of sound pulses, electrical currents, and electromagnetic fields for study of the Earth and for geological research. Forced conditions which increase the efficiency of the investigations are pointed out: forced beam ejection, modulation, integrated fields, and so forth.

The radiation of sound by fast charged particles in a medium[1] has made it possible to develop[2,3] acoustic methods of detection of charged-particle showers produced by very rare high-energy neutrinos arriving from space. On the basis of this acoustic detection a group of western physicists (De Rujula, Glashow, Wilson, and Charpak) has recently proposed[4] use of a neutrino beam produced by a super-high energy accelerator to search for useful minerals and for radiography of the Earth.[1]

Calculations have shown that instruments which will be extremely efficient for this purpose will be proton accelerators of energy $\mathscr{E}_p \approx 20-30$. TeV (1 TeV $= 10^3$ GeV $= 10^6$ MeV), which is one and one-half orders of magnitude greater then accelerators already in existence or being put into operation. Such accelerators must have a large size—a radius of 10 km or more, and must accelerate simultaneously about 10^{15} protons or more.

An accelerated beam of protons (or other nuclei) on hitting a target produces in multiple-production events a beam of pions of average energy $\sim 0.1\ \mathscr{E}_p$. However, a fraction of the pions have energy several times greater than the average, and it is just these pions which are very important for our purposes. The pions decay in flight into muons and muon neutrinos. Although at low energies the pion lifetime is $\tau_0 \approx 10^{-8}$ sec, as the result of higher energies thousands of times greater than their rest energy the pion lifetime is increased as a consequence of relativistic time dilation, and therefore the range ot decay turns out to be large: $l = \tau_0 c/\sqrt{1-\beta^2} \approx \tau_0 c \mathscr{E}_\pi/\mathscr{E}_{\pi 0}$, that is, of the order of tens of kilometers, and the emission angles are very small. In practice it is sufficient to construct a decay tunnel of length of several kilometers if one makes use of the decay of only part ($\sim 10\%$) of the pion beam. By using magnetic fields it is possible to further focus the meson beam so as to provide a small divergence of the neutrino beam, as small as $\theta \approx 10^{-5}$ rad. Even at a distance of 10^3 km this gives a neutrino beam of diameter of the order of 10 m. This is a good resolution which will permit identification of the properties of layers of earth. The total number of neutrinos in a beam burst with the maximum accelerator parameters[4] has been taken by the author as typical and as a starting point for estimates.

If we specify a neutrino spectrum of this type,[4] we have $dN_\nu(\mathscr{E}_\nu) \approx (N_\nu/\langle\mathscr{E}_\nu\rangle) \times e^{-\mathscr{E}_\nu/\langle\mathscr{E}_\nu\rangle} d\mathscr{E}_\nu$, where N_ν is the total number of neutrinos:

$$N_\nu = \int_0^\infty dN_\nu;$$

$\langle\mathscr{E}_\nu\rangle$ is the average neutrino energy (for the spectrum of Ref. 4 $N_\nu \approx 3\cdot 10^{13}$ and $\langle\mathscr{E}_\nu\rangle \sim 1-2$ TeV). The value of the energy flux $\Phi \sim \mathscr{E}_\nu^n$ integrated over the spectrum is

$$\Phi_{\text{int}} = \int_0^\infty \mathscr{E}_\nu^n\, dN_\nu \approx (n!)\, \langle\mathscr{E}_\nu\rangle^n N_\nu,$$

i.e., if we specify the total number of neutrinos, to obtain average values $\langle\Phi\rangle$ we can directly take the unaveraged value at $\mathscr{E}_\nu = {}^n\sqrt{n!}\langle\mathscr{E}_\nu\rangle$. For example, for $n=2$ we have $\mathscr{E}_{\nu_{\text{eff}}} \approx 1.4\langle\mathscr{E}_\nu\rangle$, for $n=3$ we have $\mathscr{E}_{\nu_{\text{eff}}} \approx 1.8\langle\mathscr{E}_\nu\rangle$, and so forth. This increase is very important in our case.

High energies of the accelerated particles are necessary not only for creation of a narrowly directed beam, but also for increasing the interaction of the neutrinos with matter. The point is that the cross section for interaction of neutrinos with nucleons over a wide energy range is proportional to their energy $\sigma_{\nu n} \approx 10^{-35} \times \mathscr{E}_\nu$ (GeV). Thus, while for neutrinos of low and intermediate energies the Earth's sphere is transparent, high-energy neutrinos are appreciably attenuated (the range is $L_\nu \approx m_p/\rho\sigma_{\nu n} \sim 1/\mathscr{E}_\nu$, where ρ is the density of matter and m_p is the nucleon mass). This also permits investigation of the density distribution inside the Earth if $L_\nu \approx 3\cdot 10^4 - 10^5$ km.

Increase of the nuetrino interaction is extremely important also for increase of the bulk energy release, on which the magnitude of the sound pulse depends. Indeed, the density of the energy release q determines the pulsed thermal expansion of the material (the analog of the thermal generation of sound in pulsed heating of solids) $\Delta\rho/\rho \approx \alpha_T \Delta T$, and here

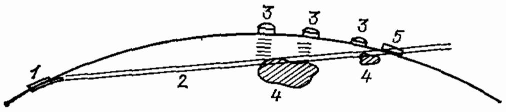

FIG. 1. Neutrino geology. 1—accelerator with bending of the beam, 2—neutrino beam, 3—sound detectors, 4—layers of useful minerals, 5—muon detector.

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[1] This question was the subject of the report by B. A. Dolgoshein at the Joint Scientific Session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the USSR Academy of Sciences on 28 December 1983.

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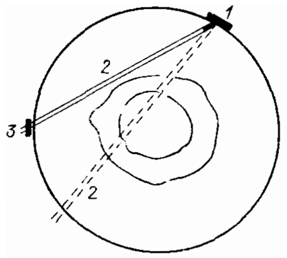

FIG. 2. Study of the Earth with a neutrino beam. 1—accelerator, 2—neutrino beam, 3—neutrino-beam detector.

the pressure increases: $\Delta p \sim \Delta \rho \cdot c_s^2$, where c_s is the velocity of sound and α_T is the volume coefficient of thermal expansion. Since $\Delta T \approx q/C\rho$, where C is the specific heat and ρ is the density of the medium, we obtain $\Delta p \approx \alpha_T c_s^2 q/C = \Gamma q$, where Γ is the so-called Grüneisen coefficient. The amplitude of the initial pressure of the sound wave is extremely close to the excess pressure which arises, $p_{s0} \sim \Delta p$. For a cylindrical geometry of the beam the amplitude of sound at a distance R from the beam axis is $p_s(R) \approx p_{s0}\sqrt{a/R}$, where a is the radius of the region of initial energy release, and in this case the characteristic pulse duration is $t_s \sim a/c_s \approx 10^{-2}$ sec. It is already clear from this that knowing t_s and a we can determine c_s and can to a certain extent characterize the properties of the material.

If we set $q \approx N_\nu \sigma_\nu \mathscr{E}_\nu n_a/\pi a^2$, we obtain for $\sigma_\nu \approx \mathscr{E}_\nu$ a dependence $p_{s0} \sim N_\nu \mathscr{E}_\nu^2/a^2$, i.e., we can see at once the advantage of going to higher energies, which produce a rapid increase of p_s as the result of the increase of $\sigma_\nu \mathscr{E}_\nu \sim \mathscr{E}_\nu^2$, the increase of N_ν, and the decrease of a. This increase of the sound pulse is very desirable since even at high energies of the accelerator[4] the sound amplitude is very small, $p_{s0} \approx N_\nu \mathscr{E}_\nu/L_\nu \pi a^2 \approx 3 \cdot 10^{-3}$ absolute units for typical conditions of the experiment[4] and for a number of neutrinos per "burst" from the accelerator $N_\nu \approx 3 \cdot 10^{13}$, $\mathscr{E}_{\nu_{\text{eff}}} \approx 2$–$4$ TeV, a neutrino range $L_\nu \approx 3 \cdot 10^4$–$10^5$ km, and a beam radius $a \approx 10$ m. At a distance R of the order of kilometers this will give $p_s \approx 3 \cdot 10^{-4}$ absolute units, which is small in comparison with the noise in the necessary region of the sound-frequency spectrum (10–100 Hz). However, there are factors and possibilities which assist the separation of the useful signal from the noise background, as follows:

1. The strict repetition of the signal with cyclical operation of the accelerator.
2. The possibility of selection of signals on the basis of direction and the point of production, since the time and place of generation of the pulse are known (detectors focused to a certain point in the interior).
3. Selection of signals of known or expected shape.
4. Use of systems which record coincidences of pulses, and so forth.

What kind of information can the sound pulses carry?

First of all, as a result of the small attenuation and distortion of the shape at frequencies 10–100 Hz it is possible to obtain information from the amplitude of the sound (the local Grüneisen coefficient or the local properties of the neutrino interaction) and from the shape of the pulse (duration, form of reverberation, and nature of the decay). Second, by shifting the neutrino beam and measuring the change in delay of the sound pulse it is possible to evaluate the effective velocity of sound and from it to characterize the properties of the medium and the change of these properties with depth. The type of sound—longitudinal or transverse—also can characterize the medium.

The sound detector can be of the multielement type that is used in seismic prospecting, which will permit comparison of pulses detected by different elements and selection of the useful ones on the basis of their arrival in the necessary time intervals, using the difference in times of arrival. This detector should be mobile and either have good acoustic contact with the Earth's surface or should detect surface vibrations by means of a contact-free technique.

Acoustic prospecting by means of a depth source of this type may turn out to be more efficient than seismic prospecting which is used at the present time. Although seismic prospecting makes use of simpler sources of sound (explosions, electrical sources of sound, and vibrators), the large background produced by reflections from the boundaries of the regions adjacent to the sound source make it very difficult to identify the acoustic data.

Another possibility of geological searching for minerals by means of a neutrino beam lies in the use of high-energy muons produced in interaction of neutrinos with nuclei and having ranges which reach kilometers. Such muons accompany the entire path of the neutrino beam, being produced, slowed down, and disappearing in the medium. Their equilibrium number determined by the balance between production and disappearance will depend on the properties of the material. Therefore by detecting muons at the surface of the Earth at various places it is possible to deduce the effective atomic number of the medium in the path of the beam. Scattering of the beam of muons also disturbs their distribution and can characterize the properties of the medium in their path.

It is interesting to note that some years ago[5] it was proposed to use cosmic-ray muons for evaluation of the rock in measurements in mines and that this was tested in practice.

A narrow neutrino beam will also permit tomographic studies of the distribution of material along the diameter and chords, by studying the absorption of the beam. Selection of the neutrino energy will permit the neutrino absorption to be varied over a wide range, and will make possible the choice of optimal conditions and optimal information on the type of material in the neutrino path. Such suggestions were made also by Zatsepin and Volkova.[6]

Detection of the neutrino beam after its passage can be accomplished by means of recently developed methods of measurement of showers in large volumes of matter. These methods use optical detection either of luminescence of the Cherenkov radiation produced by the secondary particles in the natural media or in special blocks (an optical DUMAND[2]), or of the flash in the atmosphere from showers

[2] This project is the subject of the following articles: V. S. Berezinskiĭ and G. T. Zatsepin, Usp. Fiz. Nauk **122**, 3 (1977) [Sov. Phys. Uspeki **20**, 361 (1977)]; John G. Learned and David Eichler, A deep-sea neutrino telescope, Scientific American **244** (2), 138–152 (February 1981) [Russ. Transl. in Usp. Fiz. Nauk **137**, 449 (1982)].

produced by neutrinos which have passed through the Earth (see the variant "Chalons"[7] recently proposed by Nikol'skiĭ and Tsarev), or acoustic detection of showers form neutrino interactions.[2,3]

On of the most complicated questions—changing the direction of the neutrino beam through large angles by bending the proton beam—will require an extremely complicated and expensive arrangement of the decay tunnel. So far there exist only rather fantastic plans[4] for floating accelerators or floating exit channels.

In a recent article by Tsarev and his colleagues it was shown[8] that if one uses neutrinos not from pion decay but from decay of charmed particles (and at proton energies $\mathscr{E}_p \approx 10$–20 TeV there can be at least as many of these as there are pions which have decayed), then as the result of the small decay range it will be possible to get along with a much smaller decay channel. However, as a result of the large rest mass of charmed particles and consequently the less relativistic behavior and the impossibility of focusing to a small size, the divergence and radius of the neutrino beam will be several factors of ten larger.

It is worth mentioning that in the plan of Ref. 4 it will be necessary to scan the proton beam itself, and it will be impossible to turn the pion beam without losing its concentration (the pions have a spectrum of energies and in being turned by a magnetic field will form a fan).

However, in the report by Dolgoshein mentioned above, the described a very interesting possibility proposed by A. N. Skrinskiĭ of the Nuclear Physics Institute at Novosibirsk, for creation of a linear pion accelerator up to energies ~ 1 TeV (protons accelerated to $\mathscr{E}_p \approx 100$ GeV produce pions with energy $\mathscr{E}_\pi \approx 10$ GeV which are themselves accelerated and in a length of several kilometers will reach the necessary energies $\mathscr{E}_\pi \approx 1$ TeV). Here the pion beam will be obtained in monochromatic form and can be turned by a magnetic field, which is several times easier than in the plan of Ref. 4 in which it is necessary to turn protons of much higher energies. The high initial energy of the produced pions and the rapid acceleration make the decay during acceleration unimportant. Such an accelerator can give bursts of 10^{12} pions with a repetition frequency of 10^2 Hz. As before, one of the difficulties is the achievement of a mobile decay channel.

However, a neutrino beam can produce not only thermoacoustic signals. A very recent article by the present author[9] discusses the electromagnetic fields produced by a high-energy neutrino beam in matter.

It turns out that the neutrinos produce muons with an excess of one sign of charge.

Usually, as the result of the conditions of focusing of the pions, pions of a definite sign of charge will be emitted in the decay channel. Therefore in their decay one obtains either muon neutrinos (from π_+) or muon antineutrinos (from π_-). Such neutrino beams give muon beams of definite signs of charge: only μ_- from neutrinos and only μ_+ form antineutrinos. Here as a result of the difference in the cross sections for muon production (negative muons are preferentially produced, $\sigma_{\nu\mu_-} \approx \sigma_{\bar{\nu}\mu_+}$, on the average per nucleon; see for example Ref. 10) and excess of the muon charge is produced even in the case of a mixture of ν and $\bar{\nu}$.

If one is given a neutrino flux intensity $\dot{N}_\nu$, then the quasi-equilibrium current produced by muons is $\mathscr{I}_\mu \simeq e\dot{N}_\nu L_\mu / L_\nu$, where L_μ is the muon range and L_ν is the neutrino range. The ratio $L_\mu / L_\nu \sim \mathscr{E}_\nu^2$ is almost independent of ρ, since $L_\mu \sim \mathscr{E}/\rho$ and $L_\nu \sim 1/\mathscr{E}\rho$. (We recall the necessity of averaging over the spectrum!) In our case $L_\mu \sim 1$–2 km and $L_\nu \sim 3 \cdot 10^4$–10^5 km, depending on the form of the function which is averaged.

A moving muon bunch contains many particles, $N_\mu \sim N_\nu L_\mu / L_\nu$, and produces strong coherent radiation in the region of wavelength greater than the longitudinal size of the bunch $l \approx cT$, where T is the time of emission of all the particles or of a group of particles. This time can be varied over a wide range: the time of revolution of a bunch filling the accelerator ring is $T_{2\pi} \approx 10^2$ μsec. With a gradual spill or a spill in batches one can have $T \gg T_{2\pi}$, but as the result of either compression or modulation of the beam a flux $\dot{N} \gg N / T_{2\pi}$ is possible and the spill time can be $T \approx (10^{-1}$–$10^{-2}) T_{2\pi}$. For a forced dump ($T \gtrsim 1$ μsec) we obtain $\mathscr{I}_\mu \approx e\dot{N}_\nu L_\mu / L_\nu \approx 0.3$ mA; for $T_{2\pi} \approx 100$ μsec we have $\mathscr{I}_\mu \approx 3$ μA.

This current can be detected on the basis of the magnetic field $H\,(\text{oe}) \approx 0.2 \mathscr{I}(\text{A})/R \sim \dot{N}_\nu$ and on the basis of the induction fields

$$\mathscr{E}_{\text{ind}} \approx \frac{1}{c} \dot{H} S \sim \ddot{N}_\nu$$

in the near zone (at distances $R \ll cT$).

In addition to the moving excess muon charge there should be an excess moving charge in the showers[11,12] produced by cascades in interaction of neutrinos with nuclei. This excess is due[11] to the inclusion of δ electrons and Compton electrons in the shower and to annihilation in flight of positrons. In each shower the excess number of particles is $n_{\text{exc}} \approx (0.1$–$0.2) n_{\max}$, where $n_{\max} \approx \mathscr{E}_\nu / 10^2$ MeV. Therefore this excess charge is $N_{\text{exc}} \approx n_{\text{exc}} (L_c/3) N_\nu / L_\nu$, where L_c is the cascade length ($L_c \approx 3$ m). The ratio of the excess charges is $N_e / N_\mu \sim n_{\text{exc}} (L_c/3)/L_\mu \approx 5$–$10$, i.e., the excess charge of the showers can exceed that of the muons. If on the basis of a different, greatly simplified model we assume that the total displacement of all charges is determined by the ionization loss, $L_{\text{eff}} \approx \mathscr{E}/(\mathrm{d}E_1/\mathrm{d}x)$, then the shower dipole moment $P_c \lesssim eL_{\text{eff}} \sim e\mathscr{E}/(\mathrm{d}E_1/\mathrm{d}x_{e)}$, and for muons $P_\mu \approx eL_\mu \approx e\mathscr{E}(\mathrm{d}E_1/\mathrm{d}x)_\mu$, i.e., the contributions of the shower and the muons to the current will be comparable. The main contribution to creation of an excess directed moving charge occurs at the maximum of development of the shower and beyond it and is from γ rays which produce Compton electrons moving directionally with energies of the order of tens of MeV.

The currents should be weakly compensated by the background conductivity of rock with good dielectric properties ($\sigma \lesssim 10^6$–10^7 absolute units and $\varepsilon \approx 10$), in order that the reverse current not be able to attenuate appreciably the directional movement of the charge.

Motion of the charges faster than the velocity of light in the medium should produce a flash of Cherenkov radiation. The lower limit of the radiated power is

$$w \approx \frac{N^2e^2\omega\Delta\omega}{c} \sim \frac{(2\pi)^2 N^2e^2}{cT^2}.$$

For $N \sim 10^{10}$ and $T \sim 1$ μsec–10^2 μsec we obtain $w \approx 3$ mW–0.3 μW. This is a lower estimate for a very diffuse cone of radiation (with a sharp cone the field strength of the radiation is much greater at the front of a cone with angle $\varphi \approx \cos^{-1}(1/n)$).

In material with high Q (salt, ice, air, etc.) the radiated power can be increased substantially in going to short wavelengths, for example, the decimeter range. With emission of a chain of bunches one can have coherence and generation of narrow-band radiation. These effects can be used also for detection of a neutrino beam.

Note that the method proposed some time ago[11,12] for radio detection of rare particles in large volumes of natural media (including ice) with low absorption of the radio waves has been suggested again recently in Ref. 13.

Integrated mechanisms are possible for creation of electromagnetic fields. For example, the longitudinal nonuniformity of the currents $\partial\mathcal{J}/\partial z$ can result in the formation of electric charges:

$$\frac{\partial\mathcal{J}}{\partial z} = \dot{Q}_1 + \frac{2\pi\sigma}{\varepsilon} Q_1,$$

where Q_1 is the running charge. For good dielectrics ($T\sigma < 1$) the charge Q_1 gives at a distance $R \lesssim l$ a field $E \sim 2Q_1/R$. With a dimension of the inhomogeneity of the current $l < 1$ km we obtain

$$E \sim \frac{2eN_\nu}{lR}\frac{L_\mu}{L_\nu} \approx 1\ \mu\text{V}/m.$$

By studying the nature of the electromagnetic pulses (shape and delay) and the distortions of the fields produced by internal field sources it is possible to carry out much more efficiently (as a result of the greater certainty in the place of production and path of the signal) electromagnetic radiography[14,15] of rocks by means of a system of probes located on the Earth's surface or in inexpensive narrow holes. Repetition of the pulses facilitates their identification against the noise background, which is very important in view of the possible absorption in the near-surface layers. Such radiofrequency studies are usually carried out in the kHz–MHz range, which is easily accomplished in accelerators with direct, extended, or forced ejection of the beam. Forced ejection of a beam during short time intervals is possible, for example, on increasing the path in front of the moving particles (by application of a small magnetic field or electric field, etc.): if the particle-orbit radius differs by ΔR (to remain within the small dimensions of the vacuum chamber we shall take $\Delta R \sim 3$ cm), then the path difference per turn is $2\pi\Delta R$ and one needs a number of revolutions η for the ring-shaped bunch to shrink:

$$2\pi\Delta R\eta \sim 2\pi R, \quad \text{i.e.,} \quad \eta \approx \frac{R}{\Delta R} \sim 3\cdot 10^5.$$

For a time of resolution $T_{2\pi} \approx 2\cdot 10^{-4}$ sec this requires 60 seconds. It is possible to compress the bunch and increase the path with oscillations of the particles and by other means.

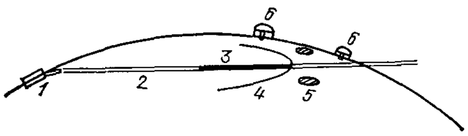

FIG. 3. Electromagnetic radiography of rock by a neutrino beam. 1—accelerator, 2—neutrino beam, 3—bunch of excess moving muon and electron charges, 4—cone of radiation, 5—useful minerals, 6—probes of the electromagnetic field on the Earth's surface or in holes.

Under ordinary conditions a bunch is modulated in density, and this also can be used to increase the spectral density of the radiation.

The intensity of electromagnetic radiation of a sequence of bunches[16] is

$$I \approx \frac{q_1^2}{c^2}\int\limits_{\varepsilon\beta^2>1}\left(1-\frac{1}{\varepsilon\beta^2}\right)\frac{\sin^2(M\omega L/2v)}{\sin^2(\omega L/2v)}\left(\frac{2v}{\omega l}\sin\frac{\omega l}{2v}\right)^2,$$
$$\left[\frac{2J_1(|\varkappa_0|a)}{|\varkappa_0|a}\right]^2\omega\,d\omega \to \frac{q_1^2}{c^2}\int\left(1-\frac{1}{\varepsilon\beta^2}\right)$$
$$\frac{\sin^2(M\omega L/2v)}{\sin^2(\omega L/2v)}\,\omega\,d\omega,$$

if the dimensions (length l and radius a) of each bunch are small in comparison with the wavelength and the distance between bunches L is arbitrary; q_1 is the charge of one bunch and M is the number of bunches, i.e., in the maxima of the spectrum a long train of bunches radiates as a single compressed bunch: $(I_\omega)_{\max} \sim (q_1M) \sim Q^2$. From this we can immediately see the conditions of coherence of the radiation of each bunch:

$$\text{transverse}: \quad |\varkappa_0|a = \frac{\omega}{c}\sqrt{\beta^2\varepsilon - 1}\,a \approx a\frac{\omega}{c}\sqrt{\varepsilon} \approx a/\lambda\!\!\!^{-}{}' < 1,$$
$$\text{longitudinal}: \quad \frac{\omega l}{2c} \approx l/2\lambda\!\!\!^{-}{}_0 < 1.$$

Let us now estimate the spectrum of acoustic radiation from a neutrino beam modulated in time.

Using the expression[2] for the pulse of pressure from the pulsed expansion of a thin heated running volume $V_1(t)$

$$dp = \rho_0\ddot{V}_1\left(t - \frac{R}{c_s}\right)dz\cdot\frac{1}{2\pi R}$$

for expansion in time less than the period of the waves received

$$\ddot{V}_{1\omega} = \frac{i\omega}{2\pi}\Delta V_1 e^{i\omega(t_0 - R/c_s)},$$

where the charge of volume is $\Delta V_1 \approx \alpha_T V_1 \Delta T \sim \alpha_T Q_1/Cp$, Q_{1n} is the running energy release from one nth beam pulse, α_T is the thermal expansion coefficient, C is the specific heat of the medium, and c_s is the velocity of sound, we obtain for the case

$$R \approx R_0 + \frac{z^2}{2R_0}, \quad \int\limits_{-\infty}^{\infty} e^{-i\gamma y^2}dy = \frac{1}{\sqrt{\gamma}}\sqrt{\frac{\pi}{2}}(1-i),$$
$$p_{\omega n} = \frac{\omega^{1/2}\sqrt{c_s}}{4\pi^{3/2}\sqrt{R_0}}\frac{\alpha_T}{C}Q_{1n}(1+i)e^{i\omega R_0/c_s}e^{i\omega t_n}.$$

Summing the Fourier components from several pulses traveling through time intervals τ, we obtain the combined spectrum

$$p_\omega = \sum_{n=1}^{M} p_{\omega n} = \sum_{n=1}^{M} e^{i\omega\tau n} p_{\omega 1},$$

that is,

$$|p_\omega| = \left| \frac{\sin(M\omega\tau/2)}{\sin(\omega\tau/2)} \right| |p_{\omega 1}|,$$

where M is the total number of pulses in a train, that is, intense lines appear in the spectrum when $\omega\tau/2 = m\pi$ and then $|p_\omega| \sim MQ_{1n} \sim Q_1$, where Q_1 is the total running energy release. The multipulse and narrow-band nature of the radiation facilitates detection and separation from background not only as the result of multiple recreation of the conditions, but also as the result of the phase relations.

We note the possibility of use of transportable pulsed high-power neutrino sources[17] ($N_\nu \sim 10^{17}$–10^{18}) of lower energies and lower directivities ($\theta \lesssim 0.3$) for probing at smaller distances. However, large accelerators give better resolution and global scales of search investigations.

In concluding this brief review of possibilities, we arrive at the conclusion that there is great practical promise for accelerators at superhigh energies. Such accelerators undoubtedly will be built, and their coming on stream can be very productive for nuclear physics and for practical applications.

The project of neutrino geophysical and geological investigations appears to us to be an important and striking endeavor to introduce the technology of nuclear physics into the economic structure, perhaps on the largest scale and with the greatest significance since the time of achievement of the peaceful and military uses of nuclear energy.

Our discussion also supports other possibilities of use of neutrino beams at large distances and the possibility of setting up direct physical experiments on neutrino oscillations and on new types and new channels of interaction.

The possibilities of practical application may lead to new and much more active paths to the development of nuclear physics and the technology of high-energy particles, which will accelerate the rate of development of physics in this important area.

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