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Measurement of Neutrino Oscillations in Realistic Underground Experiments.

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Summary. — We conside the possibility of investigating neutrino oscillations in a realistic environment. We discuss theoretical uncertainties coming from flux calculations, geomagnetic effects and propagation through matter, as well as the capability of identifying the neutrino-induced events in real apparata.

PACS. 94.40. – Cosmic rays.

1. – Introduction.

The use of atmospheric cosmic-ray neutrinos in underground experiments for investigating neutrino oscillations could in principle allow us to explore a region of parameter space beyond that accessible in reactor or accelerator experiments.

Unfortunately, many limitations prevent us from reaching the nominal high sensitivity deriving from the long oscillation path (*i.e.* the Earth diameter $D \sim 10^4$ km).

First, the low statistics ineherent in this kind of experiments makes small mixing angles not accessible. Furthermore, an average over the neutrino energy spectrum and neutrino directions, *i.e.* over oscillation lengths, is unavoidable: in particular, the effect of averaging over directions is much larger than the averaging over source dimensions.

The last limitation arises because of the matter. The different indices of refraction in matter for ν_μ and ν_e, generated by the charged-current contributions to elastic ν_e-e scattering, lead to a decoherence of the ν_μ and ν_e components after a characteristic length of ~ 9000 km in the Earth.

2. – Experimental possibilities.

To simplify the interpretation of the results we limit ourselves to the case of only two neutrino flavours, namely ν_μ and ν_e; an underground experiment can thus record the disappearance of ν_μ or the variation of the ratio ν_μ/ν_e.

In the first case the experiment measures the flux of muons produced by neutrinos in the surrounding rock or inside the apparatus, in the latter only events generated in the detector by ν_μ or ν_e can be used.

The disappearance method needs the knowledge of the expected flux and hence is affected by uncertainties of the order of $(10 \div 20)\%$, as confirmed also from results of large nucleon decay experiments.

The influence of the Earth magnetic field, as well as that of solar wind, adds further uncertainties to the calculation of the low-energy part of the spectrum.

The μ angular distribution and the ratio ν_μ/ν_e are, however, less sensitive to systematic uncertainties. In fact, the energy of parent neutrino for muons traversing an underground apparatus is high enough ($E_\nu \geqslant 10$ GeV) to allow neglecting geomagnetic effects, and the comparison between different path lengths makes unnecessary an absolute monitor on the flux, provided the angular distribution is known with sufficient accuracy.

The ratio ν_μ/ν_e is obviously less dependent on theoretical uncertainties.

Two final remarks on experimental possibilities are in order.

A direct comparison of the downward and upward neutrino fluxes using muons produced in the rock is difficult, since, at the deepness of the existing and proposed large underground detectors, the cosmic muon background is too high even near the horizontal direction.

In addition, the energy of neutrinos that produce muonic events contained in a detector of reasonable size is very low, so the angle between the produced muon and the parent neutrino is large, making the distinction between up and down directed neutrinos less efficient.

3. – Sensitivity.

We have considered two types of experiments: the first refers to the proposed large-area detector MACRO (1) and measures the angular distribution of the μ-induced upgoing muons produced in the rock; the second is an ideal apparatus of very large fiducial active mass ($M = 10$ kton) capable of detecting and identifying all the leptons produced inside its volume by ν_μ and ν_e with energy above $E_\nu \geqslant 0.5$ GeV.

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(1) MACRO Proposal: November 1984, Frascati (unpublished).

We have performed a complete Monte Carlo computation, including generation, transport and tracking of leptons. The ν_μ flux is taken from ref. (2), by assuming equal contribution for ν_μ and $\bar{\nu}_\mu$ and $\Phi(\nu_e) = 0.2 \times \Phi(\nu_\mu)$. The interaction cross-section includes quasi-elastic, Δ and inelastic channels. The survival probability for ν_μ is

$$P(\nu_\mu \to \nu_\mu) = 1 - (1 - \varrho) \sin^2(2\theta) \sin^2(\pi L/l_v) \tag{1}$$

in vacuum, and

$$P(\nu_\mu \to \nu_\mu) = 1 - (1 - \varrho) \sin^2(2\theta)(l_m/l_v)^2 \sin^2(\pi L/l_m) \tag{2}$$

in matter.

In the above formulae, θ is the vacuum mixing angle, ϱ the ratio ν_e/ν_μ, $l_v = 2.5E/(m_1^2 - m_2^2)$ (oscillation length in vacuum), $l_0 = 2\pi/GN_e = 9 \cdot 10^3$ km and

$$l_m = l_v(1 + (l_v/l_0)^2 \mp 2l_v/l_0 \cos 2\theta)^{-\frac{1}{2}} \tag{3}$$

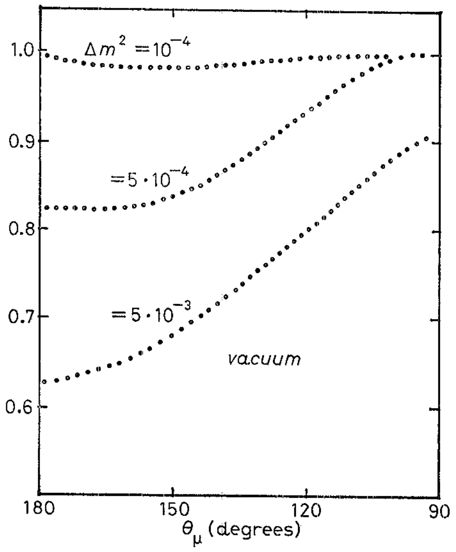

Fig. 1.

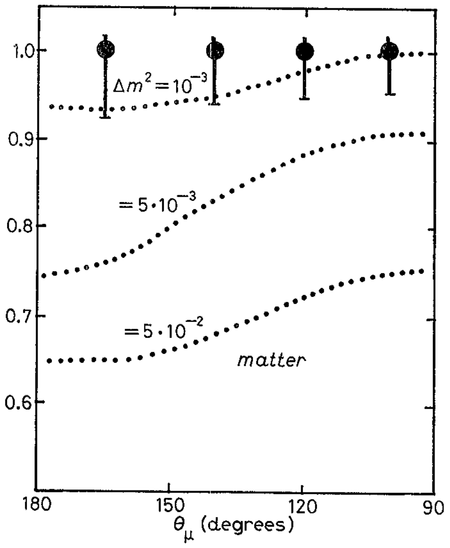

Fig. 2.

Fig. 1. – Modulation factor in MACRO, only vacuum oscillations.

Fig. 2. – Modulation factor with matter effects taken into account. Error bars refer to 3 years of data taking.

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(2) L. V. VOLKOVA: *Sov. J. Nucl. Phys.*, **31**, 784 (1980).

is the oscillation length in matter (³). The signs refer to neutrino and antineutrino, respectively.

Note that in matter the probability, for $\sin^2 2\theta \neq 1$, depends on the sign of Δm^2; in addition it is no longer true that the maximum of oscillation probability occurs, for every E_ν and Δm^2, at $\sin^2 2\theta = 1$.

In the case of MACRO a μ must traverse the detector with a minimum track length to allow the determination of the verse of motion by time-of-flight measurement. The median energy of parent neutrinos is ~60 GeV and the mean ν-μ angle is ~3.5°.

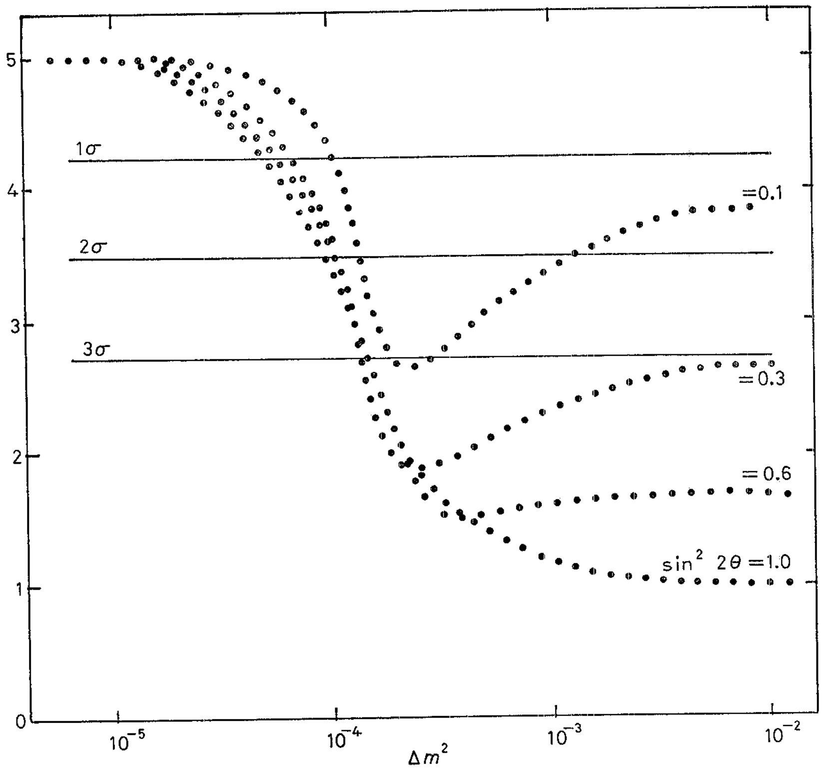

Fig. 3. – Ratio between μ-events and e-events produced inside a detector as a function of positive Δm^2 for various mixing angles. The statistical limits refer to a 30 kton × year exposure time.

The modulation factor, defined as the ratio between the measured and the expected angular distribution of the detected muons, is shown, for various Δm^2 and at maximum mixing, in fig. 1 and 2.

Matter effects reduce the sensitivity in Δm^2 by about an order of magnitude.

(³) L. WOLFENSTEIN: *Phys. Rev. D*, **17**, 2369 (1978).

The error bars indicated in fig. 2 correspond to about 3 years of exposure. For $\Delta m^2 > 5 \cdot 10^{-2}$ the modulation factor becomes again nearly flat, giving the upper limit for this experiment.

In the ideal experiment the neutrino energy responsible for the detected leptons is much lower (of the order of 1 GeV), and the ν-lepton angle is very large (~ 40°); therefore, only in about the 25 % of the events it is possible to distinguish upgoing from downgoing neutrinos.

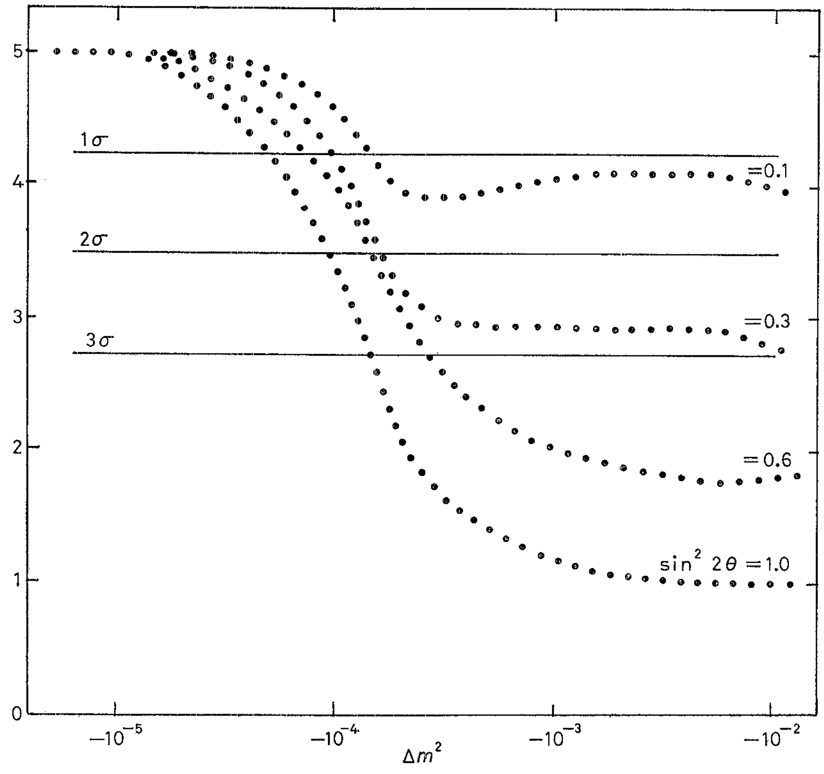

Fig. 4. – Like fig. 3 for negative Δm^2.

Assuming that all the events generated in the detector are useful for the analysis even if not fully contained, we calculated the decrease of the ratio μ/e with Δm^2.

A lower cut at $E_\nu = 0.5$ GeV has been applied for full efficiency identification of μ and e.

The result is shown in fig. 3 and 4 together with the statistical limits corresponding to a 3 years experiment; it has been assumed that the ratio μ/e for the downward neutrino gives the normalization in the absence of oscillations.

4. – Conclusions.

It has been shown that underground experiments with realistic size and in a reasonable time could reach the limit of about 10^{-4} in Δm^2 at maximal mixing, but small mixing angles, $\sin^2 2\theta$ less than 0.2, remain outside the experimental possibilities, even for very ambitious detectors.

● RIASSUNTO

Si studiano le reali possibilità di esperimenti sotterranei nella ricerca di eventuali oscillazioni di neutrini. Sono discusse le imprecisioni derivanti dal calcolo teorico del flusso aspettato e gli effetti geomagnetici e di propagazione attraverso la materia. Si tiene infine conto della capacità di apparati reali nella identificazione di eventi indotti da neutrini.

Измерения нейтринных осцилляций в реальных подземных экспериментах.

Резюме (*). — Мы рассматриваем возможность исследования нейтринных осцилляций в реальных подземных экспериментах. Мы обсуждаем теоретические неопределенности, связанные с вычислениями потока, геомагнитными эффектами и распространением через вещество. Также рассматривается возможность идентификации событий, индуцированных нейтрино, с помощью существующей аппаратуры.

(*) *Переведено редакцией.*