EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ON THE POSSIBILITY OF USING HIGH-ENERGY NEUTRINOS TO STUDY THE EARTH'S INTERIOR

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It has been experimentally found at CERN that the interaction cross-section $\sigma_{\nu_\mu}(E)$ of neutrinos against protons[1])

$$\nu_\mu + p \rightarrow \text{anything} \quad , \qquad (1)$$

increases linearly with the laboratory energy E of the incoming neutrino: the measurements have been done using neutrinos of energy up to 10 GeV.

Quantitatively, taking into account also the contribution of the so-called "neutral current" term (which seems to contribute for about 25%), $\sigma_{\nu_\mu}(E)$ for process (1) can be written[2-4]) *):

$$\sigma_{\nu_\mu}(E) \simeq 10^{-38} \cdot E \text{ cm}^2 \quad , \qquad (2)$$

where E is the laboratory energy of the incoming neutrino in GeV.

If expression (2) keeps valid until $E \simeq 2000$ GeV**), then $\sigma_{\nu_\mu}(E)$ reaches the value of 2×10^{-35} cm^2. Although hypothetical, such a large possible value for the cross-section σ_{ν_μ} has led us to investigate the possibility of using high-energy neutrinos in order to study the density of the Earth far below the crust.

The purpose of this letter is to present some results of these speculations.

So far, most information concerning the interior of the Earth has been obtained by studying the propagation of seismic waves through the Earth[5]); these waves, which are of longitudinal or transversal type, are propagated with a velocity given by

$$v_p(R) = \sqrt{\frac{K(R) + \frac{3}{4}\mu(R)}{\rho(R)}} \quad \text{for longitudinal waves} \qquad (3)$$

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*) The first results of an experiment to study process (1) running at the National Accelerator Laboratory (Batavia), using neutrinos of energy in the range 100 GeV, does not seem to be inconsistent with a linearly rising $\sigma_{\nu_\mu}(E)$ with E: muonless interactions of neutrinos have been definitely established to occur also at these large values of E (Ref. 4, and C. Rubbia, private communication).

**) Nowadays such an extrapolation does not appear unreasonable; in any case, if an intermediate boson of mass M_b would exist, then one expects deviations from the value given by formula (2) at $E \simeq M_b^2/2$; for $M_b \simeq 60$ GeV, $E \simeq 1800$ GeV.

$$v_s(R) = \sqrt{\frac{\mu(R)}{\rho(R)}} \quad \text{for transversal waves ,} \qquad (4)$$

where

R is the distance from the Earth's centre to a point of the Earth's interior;

$\mu(R)$ is the rigidity of matter at R;

$\rho(R)$ is the density of matter at R;

K(R) is the bulk-modulus of matter at R.

Knowing at each R only the two velocities (3) and (4), it is not possible to deduce directly the three quantities $\mu(R)$, $\rho(R)$, and K(R); a certain amount of theoretical work must be done in order to infer their values.

Table 1 gives the results of calculations made by Bullen6) for the density function $\rho(R)$ on the basis of two extreme assumptions: in the first (column A of Table 1) he assumes that the density varies smoothly throughout the entire core, whereas in the second one (column B) the density at the centre of the Earth is assumed to be 22.3 g/cm^3. In this latter case there would be a density jump of about 10 g/cm^3 between the bottom of layer E and the top of layer G (see Table 1).

In the following it will be shown that if the scaling law (2) 7) is valid up to a sufficiently large value of E [so that $\sigma_\nu(E) \simeq 10^{-35}$ cm^3] it becomes possible, by measuring the attenuation of a neutrino beam by the Earth, to establish a third independent relation which, added to Eqs. (3) and (4), permits us to infer directly the quantities ρ, μ, and K near R = 0.

Referring to Fig. 1 let us call Q the injection point, on the Earth's surface, of the high-energy neutrino beam. We will suppose this beam is pointing towards a detector which is placed at the point N(d), identified by the coordinate d, counted along the Earth's surface, between the point N(d) and the point M chosen diametrically opposite to Q (see Fig. 1).

Figure 2 gives the values of the paths P(d) in g/cm^2 as function of the positions of N(d), assuming for the density function $\rho(R)$ of the Earth's interior the two extreme functions A and B tabulated in Table 1.

For a given point N(d) the attenuation factor of a monochromatic neutrino beam, due to the path P(d), is given by

$$F = e^{-P(d)\times N_A \times \sigma_\nu(E)} , \qquad (5)$$

where N_A is the Avogadro constant.

In Table 2 are presented the values of F, as a function of E, having taken for P(d) its maximum value P(0) -- neutrinos passing through the Earth's centre.

From Table 2 it appears that, as expected, the flux of low-energy neutrinos is negligibly attenuated by the Earth's matter, whereas for sufficiently high values of E (E > 1000 GeV) the high-energy neutrino flux is attenuated by the Earth's matter by more than 10%. It is by measuring such an attenuation that one can obtain information about $\rho(R)$ near R = 0 (which is the most interesting case). From the table it is also clear that to be able to perform such an absorption measurement efficiently, E cannot be much lower than 1000 GeV [always under the assumption that expression (2) is valid at such high values of E].

To proceed further, let us calculate the intensity $I_\nu(E)$ of high-energy neutrinos (with average energy $\bar{E}$ > 1000 GeV) needed to be injected at the point Q towards M (see Fig. 1); to do so we need to fix the detector weight W and the minimum number of interactions S that one wants to detect per day in the detector at the point M. Taking S for a minimum value of 4/day and for W the value of 1000 tons, one obtains that at the injection point Q one must have a neutrino intensity

$$I_\nu\ (\bar{E} > 1000\ \mathrm{GeV}) > 10^8/\mathrm{sec} \times 10^{-4}\ \mathrm{rad}\ . \qquad (6)$$

Before discussing the quantities W and $I_\nu(E)$ we wish to fix some general requirements for the possible set-up. With regard to the detector specifically, the following general characteristics should be envisaged:

i) the detector must be able to give a rough esimate of the energy of the interacting neutrinos (use of a calorimeter-type detector) in order that a selection of high-energy neutrino interactions may safely be made;

ii) the detector must be equipped with some sufficiently fast counters in order to single out fast particles due to neutrino interactions (which will be coming from the bottom) from particles of the cosmic-ray component by a time-of-flight technique;

iii) a proper fast coincidence must be used in identifying the neutrino interactions in order to correlate (in time) the detected interaction [say at the point N(d)] with the spill-out time of the proton beam at the point Q.

One can easily check that the conditions (i) to (iii) reduce the cosmic-ray background (contributing only to the accidentals) to a negligible level.

As far as the set-up in general is concerned, we wish to describe here two possible schemes (always referring to Fig. 1).

a) Movable detector arrangement. In this case the experiment would consist in comparing the intensities of spectra of the emerging neutrino beam detected at different places N(d). More specifically, assuming that the neutrino beam has a low-energy component*), then the measurements will consist in counting at each position N(d) in the neutrino detector the number of high-energy interactions S(d) [which will be proportional to the high-energy neutrino (emerging) flux] normalized to the number of low-energy interactions, seen in the same detector (which will be almost proportional to the low-energy neutrino flux -- supposedly unattenuated); such measurements have to be repeated at different N(d) until a certain value d_m**) is reached, for which also the high-energy neutrinos are only slightly attenuated by the Earth's matter. According to Table 2, S(0) should be lower than $S(d_m)$ by an amount which will depend on the energy of the interacting neutrinos. Moreover, available statistics permitting, one should observe a rather sharp variation of S(d) around a value d = 2600 km (see Fig. 1) if hypothesis B of Table 1 is verified.

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*) Usually the neutrino energy spectrum, if particular care is not taken, has a very fast rise towards the low values of the energy.

**) From Fig. 2 one sees that this happens for $d_m \simeq 10000$ km.

Since the detector biases must be well under control (the effect being quite small), one can imagine that the best thing would be to mount the detector on a ship and move this around*).

b) Fixed detector arrangement. In this case there would be a fixed detector at a chosen point, say M; here the problem is to find out the total unattenuated neutrino spectrum in order to compare it with the spectrum seen in the detector. A possibility is to put at the injection point Q, before the neutrinos enter the Earth, a detector similar to the one used at M and measure the unattenuated neutrino spectrum. The comparison of the two spectra will give the attenuation of the high-energy component.

We now wish to make a few remarks about some of the parameters fixed during the analysis. From Table 1 it can be seen that the high-energy neutrino beams needed for such a geophysical experiment will not be available in the very near future. However, discussions are beginning with respect to the scientific merit and to the feasibility of machines accelerating protons to energies much higher than the ones now available at CERN and ANL**): the fact that the high-energy neutrinos may offer such an extraordinary and unique chance of studying the region near the Earth's core could produce another valid reason for studying the feasibility of machines accelerating protons into the multi-GeV region of energy.

With regard to $I_\nu(\bar{E})$ established by Eq. (6), this value depends mainly on the weight W of the detector; since the neutrinos arrive over a large area at N(d), then leaving out considerations of cost, it is in principle possible to cover a rather large surface with neutrino detectors and greatly increase the value of 1000 tons previously fixed for W.

Before closing this note we want to make a few comments on two of the (currently accepted) assumptions made on the properties of the neutrinos.

We have assumed that during the time the neutrinos take to pass through the Earth (about 0.04 sec), the μ_ν remain the same. We should remember that some speculations$^{8)}$ have been made that question this property -- this in view of the rather surprising experimental results, obtained by Davis$^{9)}$, who finds that the intensities of the neutrinos ν_e (in a certain region of the energy spectrum) coming from the Sun are much lower than the expected one.

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*) For CERN and NAL the region corresponding to the point M of Fig. 1 is roughly near to New Zealand and very near to the open Pacific Sea.

**) NAL 1973 Summer Study at Aspen, Colorado.

The other assumption we wish to comment on is the one referring to the value of $\sigma_\nu(E)$ *).

The value (2), used in our computation, has been obtained by observing the number of interactions, in a neutrino detector, produced by neutrinos where the energy deposited in the detector was quite high. On the other hand, if the neutrinos, because of some unknown interaction property, scatter on matter with momentum transfer small enough to have escaped all observations, but large enough to give an angular deviation of the neutrinos which is not too small when compared with the neutrino beam initial angular divergence (at the point Q), then the effect of this interaction should be taken into account in computing the expected residual neutrino flux emerging at N(d).

From what is known today, these assumptions on the properties of the neutrinos are quite likely to be fulfilled; nevertheless, the rather speculative experiment that we have been discussing here may also have some interest from the point of view of "elementary particle physics" **).

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*) Rather than the inelastic cross-section $\sigma_\nu(E)$, we need here the total cross-section $\sigma_T = \sigma_\nu(E) + \sigma_e$; σ_e being the elastic part of σ_T. It is known that if $\sigma_\nu \neq 0$ then $\sigma_e \neq 0$ 10): it is possible to show that when $\sigma_\nu(E)$, given by formula (2), approaches 10^{-34} cm^2, then σ_e begins to be an approachable fraction of σ_T.

**) To pursue only this last point of view, it is clearly not necessary to have very high energy neutrinos; the ones available at CERN and NAL are adequate (apart from intensity considerations).

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5) See, for instance, K.E. Bullen, Seismic wave transmission (Chapters C, D, E, F, and G), and J.A. Jacobs, The Earth's interior. Both articles to be found in the Encyclopedia of Physics, Vol. XLVII, Geophysics I (Springer Verlag, 1958).

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7) See, for instance, the very clear article by T.D. Lee on this subject, in Physics Today, April 1972, p. 23.

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Table 1

Limiting densities $\rho(R)$ *)

Region	Layer	R (in km)	Density in g/cm^3	
			Hypothesis A	Hypothesis B
Mantle	B	5958	3.64	3.64
	C	5871	3.88	3.90
		5771	4.11	4.14
		5571	4.46	4.52
		5371	4.65	4.71
	D	4971	4.88	4.95
		4571	5.10	5.17
		4171	5.31	5.37
		3771	5.51	5.72
		3473	5.66	5.72
		3473	9.70	9.10
Outer core	E	3371	9.9	9.20
		2871	10.5	9.8
		2371	11.1	10.3
		1871	11.6	10.8
		1479	11.9	11.1
	F	1250	12.0	
Inner core	G	0	12.3	22.3

*) Taken from the article of J.A. Jacobs (see Ref. 5)

Table 2

Value of F (see text) having assumed for the path P(d) the value P(0) of Fig. 2

E (in GeV)	F = attenuation factor	
	Hypothesis A	Hypothesis B
50	0.996	0.997
100	0.992	0.994
500	0.961	0.970
700	0.946	0.958
1000	0.934	0.941
1500	0.888	0.913
2000	0.854	0.886
2500	0.821	0.859

Figure captions

Fig. 1 : Schematized view of the experimental set-up (see text): Q, neutrino beam injection point; N(d), neutrino detector's place.

Fig. 2 : Calculated values of the paths P(d), in g/cm^2 of a beam going from Q to N(d). Curves A and B are calculated taking for the density $\rho(R)$ the values given in columns A and B, respectively, of Table 1.

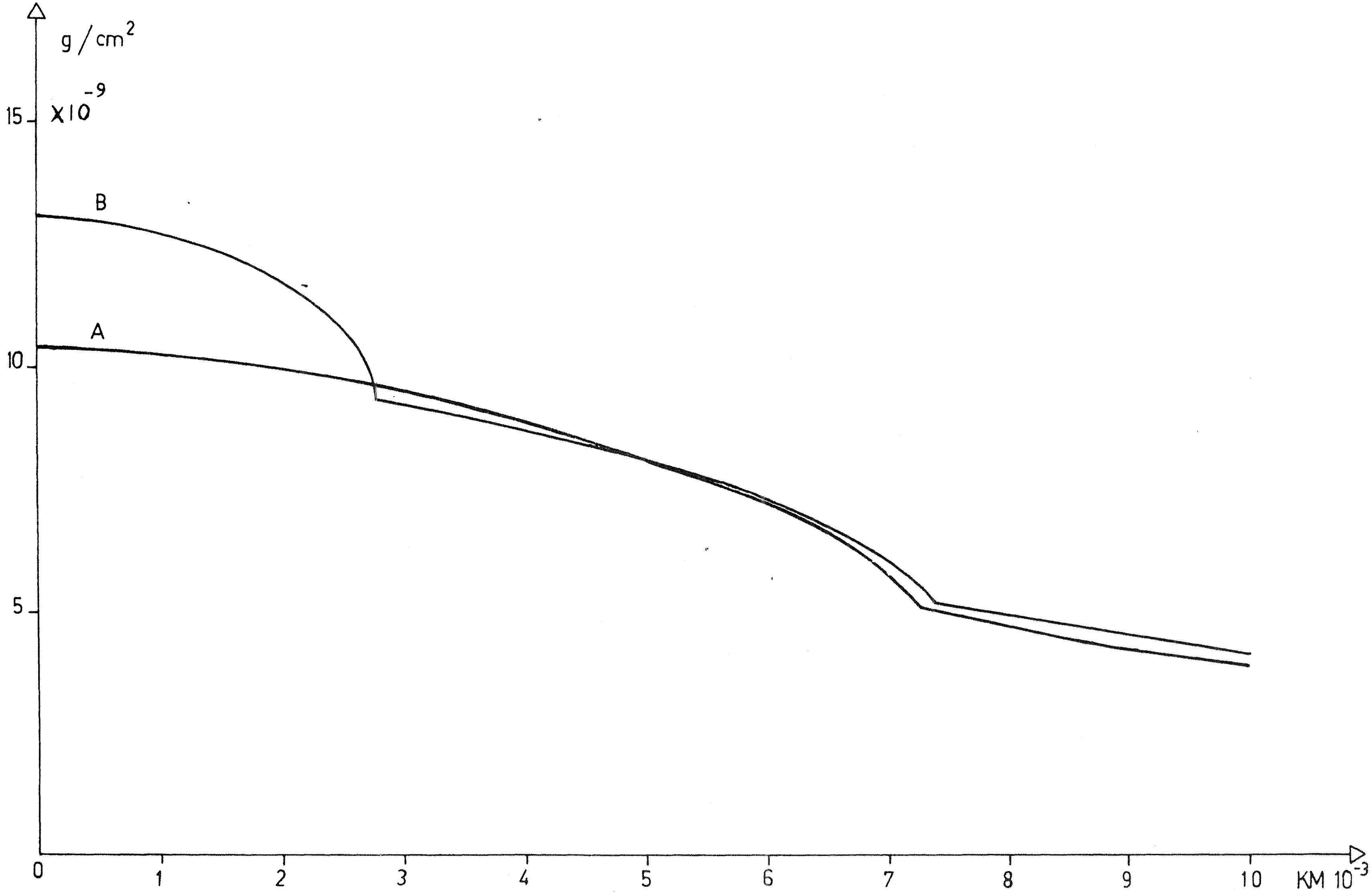

fig. 2