Geophysical prospecting using neutrino diffraction: an impossible experiment?

A. D. Fortes (1), I. G. Wood (1), and L. Oberauer (2)

(1) Department of Earth Sciences, University College London, Gower Street, London, WC1E 6BT, U. K. (2) Physik Department E15, Technische Universitat München, James-Franck Strasse 1, D-85747, Garching, Germany (andrew.fortes@ucl.ac.uk).

1. Introduction

The various techniques in use for determining the internal composition and structure of a planet depend on a combination of non-unique remote sensing (e.g., gravity, magnetism), cosmochemical models, and mineralogical data from high-P,T experiments and calculations. Even for the Earth, with excellent seismic data, we cannot uniquely determine the composition of the lower mantle and core. For the other planets in our solar system the uncertainties are even more severe. And yet it is likely that much of the Earth's interior is crystalline, as are the other terrestrial planets, icy bodies, and possibly the deep cores of the Gas Giants; it has been suggested, for example, that the cores of Uranus and Neptune are huge diamonds [1].

With an appropriate radiation source, and a suitable detector, one ought to be able to observe a diffraction pattern from the crystalline materials inside a planet. The only known particle capable of passing through so much material without significant attenuation is the neutrino, a virtually massless subatomic particle produced by nuclear reactions. We therefore explore the possibility of using either natural or artificial neutrinos to extract information on the crystalline material in a planet's interior by the technique of diffraction. Coherent scattering of neutrinos from an atomic nucleus via the weak neutral current interaction, ν + nucleon $\rightarrow$ ν + nucleon, although exceptionally small (see below), is thought to be partly responsible for the outward transfer of momentum in supernova explosions [2]. Coherent neutrino scattering allows for interference of the scattered waves and the formation of a diffraction pattern when passed through a crystal lattice. N.B. It has been suggested in previous publications

[3] that absorption of high-energy neutrinos could be used as a means of reconstructing the radial density profile of the Earth (so-called neutrino tomography). This method is still non-unique, since any number of substances could fit such a density profile.

Here, we show that the natural neutrino flux on the Earth from space is *not* a suitable radiation source for our proposed diffraction experiment; we then describe the characteristics of an ideal *artificial* neutrino radiation source, and an appropriate diffraction geometry.

2. Natural neutrinos

The largest local source of naturally occurring neutrinos is the Sun, being produced as a result of nuclear fusion reactions in its core [4]; they pass through the Earth almost unimpeded. Neutrinos are also produced in a range of astrophysical sources.

Since it is not possible to collimate neutrinos, one must measure the diffraction pattern of the entire planet in one go when using solar neutrinos. To a first approximation, the Earth - and other planets - can be treated as a polycrystalline mixture; its diffraction pattern will therefore be a powder pattern, consisting of nested diffraction cones centred along the Sun-Earth line. In order to measure the positions of Bragg peaks from the Earth's interior, one needs to scan - with an appropriate neutrino detector - in longitude (or 2-theta as a crystallographer would describe it). There are several problems with the radiation source, the sample size, and the detector geometry which need to be considered.

For the highest flux monochromatic solar neutrinos (^{7}Be neutrinos at 862 keV) the de Broglie wavelength is order 0.01 Å; using this wavelength, the bulk of the scattering from the Earth's interior would be contained in a cone extending $\sim 3^\circ$ either side of the Sun-Earth line, and the strongest peaks will be scattered barely 1°. Even with superlative directional sensitivity, the diffraction pattern will be lost in the glare of the direct neutrino beam.

Supposing that this background could be controlled somehow, there are other difficulties due to the dimensions of the scattering volume. Firstly, in order for the Bragg peaks to be sharp, the sample must subtend a small solid angle from the point of view of the detector: in other words, the detector must be placed far out in space, preferably several million kilometres away. However, even at the only viable location in space, the Earth-Sun system's L2 point, diffraction peaks from the upper mantle would still be $\sim 0.5^\circ$ wide; in addition, one would pay a severe penalty in terms of reduced flux on the detector. Furthermore, the diffracted intensity in each peak will also be dispersed by virtue of the large range of pressures to which the sample is subjected. This pressure broadening will be particularly marked for mantle materials, which experience the largest radial pressure gradient (from essentially zero to $\sim$ 135 GPa). Taking a layer of material with unit-cell volume V_0 at the outer surface and V at the inner surface, a given Bragg reflection will be spread over an angular range, $\Delta 2\theta \approx (V/V_0)^{1/3}$. For minerals in the low mantle, $V/V_0 \approx 0.8$ is a reasonable figure; this being the case, a reflection at $2\theta = 3^\circ$ would be spread over $\sim 0.2^\circ$. This problem is considerably smaller for the inner core since the radial pressure gradient is smaller ($\sim$30 GPa) and the constituent materials rather less compressible.

Having shown that diffraction using solar neutrinos is not feasible, we now consider artificially generated neutrinos.

3. Artificial neutrinos

The most important characteristic of our ideal neutrino source is that it be distinct from the astronomical (including solar) neutrino flux, so that we can measure any pattern free of background. This distinction may be in energy (i.e., $<<$ 0.5 MeV), or in intensity (i.e., $>> 10^{10}$ cm^{-2} s^{-1}). Whilst a lower energy might be preferable from a resolution standpoint, it presents a problem as the scattering cross section is proportional to the square of the energy (see below); the Earth is more transparent to lower energy neutrinos. As a matter of convenience, we would like to have the detector at the Earth's surface and not need to move it around. This means that we limit ourselves to an energy-dispersive diffraction geometry, which requires that our artificial neutron source be white rather than monochromatic. It also requires excellent energy resolution in the detectors. Finally, to limit problems due to sample size (focus and pressure gradients), it is preferable that our artificial neutrino beam illuminate relatively small volumes of the Earth's interior, of order 10^6 km^3: this also allows us potentially to study inhomogeneities in the Earth's internal structure at a useful length scale. For this reason, and to overcome natural background, the beam must be many orders of magnitude more intense than the solar flux.

Our proposed neutrino diffraction experiment consists of a nadir-pointing high-brilliance white neutrino source at a fixed point generating a beam which is passed through the centre of the Earth. Antipodal detectors act as downstream beam monitors, and a ring of detectors aligned along a great circle at an angle of 90° to the source measure the scattered flux. Assuming a directional sensitivity of $\pm 1^\circ$ for our detectors means that they can study regions $\sim$ 200 km across in the Earth's core. In order to observe a crystallographically useful range of d-spacings (1 - 3Å) at a fixed scattering angle of $2\theta = 90^\circ$, the neutrino beam must cover a range of very low energies from $\sim$ 3 - 12 keV. Since the neutrino beam is illuminating a column through the Earth, scattering from shallower depths arrives at the detector at shallower angles: for example if one wishes to study the mantle at a depth of 1500 km, one selects neutrinos arriving in the detectors at $2\theta = 53^{\circ}$ (or 127° in backscatter). If the neutrino beam were pulsed, it would be possible improve the resolution by binning the arrival times of neutrinos that have been scattered from greater depths in the Earth. The resolving power of the instrument is limited by the uncertainty in scattering angle and the energy resolution of the detector. A directional sensitivity of $\pm1^{\circ}$ leads to a d-spacing resolution of Δd/d $\approx$ 1.75 % at 2θ =90°, better resolution being achieved at higher scattering angles; Δd/d $\approx$ 0.8% at $2\theta = 127^{\circ}$, for example: these values are comparable to instruments such as POLARIS diffractometer at the ISIS neutron spallation source. Clearly, the energy resolution of the detector should be no worse than this, a challenge to present technology.

The coherent scattering cross section, $\sigma = 0.41\text{x}10^{-42}$ N^2 E^2, where N is the number of neutrons in the scattering nucleus, and E is the neutrino energy in MeV. Therefore, for iron (N = 30) illuminated with 12 keV neutrinos, σ = 5.3 x10^{-44} cm^{-2}: although $\sim$2x10^{20} times smaller than the coherent *neutron* scattering cross section of ^{56}Fe, it is offset by a sample volume which is $\sim 10^{20}$ larger than a typical neutron diffraction sample ($\sim$1cm^3). The neutrino scattering probability, P, along a 200 km-long path, L, through an iron core with a number density, Nd, of 1.43x10^{23} cm^{-3} (7 Å^3 per atom) is P = Nd σ L = 1.5 x10^{-13}. If we optimistically assume that we are able to build one hundred 1 km^2 detectors around the Earth, then we would intercept $\sim$5x10^{-6} of the scattered flux. Therefore, to achieve a scattered flux of 10^{10} cm^{-2} s^{-1} on our detectors requires that the incident neutrino beam have a flux of $\sim$1.3x10^{28} cm^{-2} s^{-1}, which is 2x10^{17} times greater than the solar flux.

The ability to do this kind of experiment is not so very far beyond our technological grasp. It is already possible to generate extremely intense beams of artificial neutrinos using synchrotrons; these so-called super-beams and beta-beams are passed along chords through the Earth to investigate the fundamental properties of neutrinos themselves [5]. It is probably only a matter of time before it is possible to produce very high intensity white neutrino beams for use in geophysical prospecting. It is also worth observing that Luca Gamberale and Flavio Fontana of the Pirelli Laboratories are currently working on speculative new ideas about neutrino production and detection [6], based on disputed results obtained twenty years ago by J. Weber [7]. Their work aims to develop small but powerful neutrino transmitters and receivers (ostensibly to send messages through the Earth), but these could find a use in planetary neutrino diffraction. One can even envisage a time when such detectors might be dispatched to investigate the interiors of other planets.

4. Summary

Neutrinos, as the only subatomic particles capable of passing right through the Earth, are the sole means of extracting crystallographic information on the substances in Earth's interior, short of taking the planet to pieces. We have shown that it is not possible to extract this crystallographic information from the scattering of solar neutrinos - the strongest local flux. Instead, we must rely on the production and detection of powerful artificial neutrino beams. The experiment we have outlined is technologically ambitious, but could allow us to solve long-standing problems relating to the structure and possible anisotropy of the inner core, and study the D" layer at the core-mantle boundary. In this way, neutrino diffraction has the potential to revolutionise our understanding of planetary physics in much the same way that helioseismology transformed our view of the Sun's interior.

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