Earth as a source of antineutrinos

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The antineutrino luminosity of the Earth, due to β decay shown by the natural radioactive nuclides, is proposed as a means to study its chemical composition.

The neutrinos and antineutrinos have an enormous mean free path. This property provides an opportunity to use them as probes to explore not only the internal structure of nucleons, but also the structure of astronomical bodies such as the sun[1] and the Earth.[2]

The neutrino luminosity of the Earth is due to electron captures in the natural radioactive nuclides ^{40}K and ^{138}La, but this fades under the more brilliant neutrino rays of the sun. However, most of the natural radioactive nuclides show negative-β decay and are antineutrino emitters; therefore, the antineutrino luminosity of the Earth may be observable and may be valuable information about the distribution of heavy elements in the interior of our planet.

The integrated intensity does not appear very unfavorable: It can be estimated to be of the order of $10^8\ \bar{\nu}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$. The main experimental problem is caused by the low energy of the terrestrial antineutrinos. The ^{238}U and ^{238}Th families give a broad energy spectrum between 0.01 and 2 MeV. The contribution of the ^{235}U family is not important. The ^{40}K decays give a rather sharp maximum near 1 MeV.

In the calculation reported here, altogether 57 radioisotopes were taken into account.

The induced β decay is a well established method of antineutrino detection, e.g.,

$$\bar{\nu}_e + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + e^+ \ .$$

This special reaction is sensitive to $E_\nu \geq 1.02$ MeV. The reaction cross section is given by

$$\sigma(\epsilon) = \frac{2\pi^2 \lambda_c^{\,3}}{ftc} \ln 2 (\epsilon - \epsilon_0)[(\epsilon - \epsilon_0)^2 - 1]^{1/2} \text{ for } \epsilon > \epsilon_0 + 1,$$

where $E = \epsilon m_e c^2$ is the energy of the antineutrino, $M(^3\mathrm{H}) - M(^3\mathrm{He}) = m_e \epsilon_0$ is the mass difference of the atoms involved, ft is the reduced half-life of the $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$ decay, and $\lambda_c = \hbar/m_e c$ is the Compton wavelength.

The induced K capture

$$\bar{\nu}_e + e^- + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H}$$

is sensitive only at a definite antineutrino energy $\epsilon = \epsilon_0 - 1$; its probability is

$$P(\epsilon) = 4\pi^3 \frac{\lambda_c^{\,3} \ln 2}{ftc} \left(\frac{Z}{137}\right)^3 \delta(\epsilon - \epsilon_0 + 1) \ .$$

[Here the Schrödinger wave function

$$|\Psi_e(0)|^2 = \frac{1}{\pi}\left(\frac{Z}{137\lambda_c}\right)^3$$

was used. For high Z values, the Dirac functions would give more accurate results.]

If the spectral intensity of the antineutrino radiation is described by $I(\epsilon)d\epsilon$ in $\bar{\nu}_e/\mathrm{cm}^2\mathrm{sec}$ units, then the mean lifetime of the otherwise stable nucleus ^{3}He in the radiation field of the Earth is given by

$$T^{-1} = \int_{\epsilon_0+1}^{\infty} \sigma(\epsilon) I(\epsilon) d\epsilon + \int_0^{\infty} w(\epsilon) c I(\epsilon) d\epsilon \ ,$$

i.e.,

$$T^{-1} = \frac{4\pi^3 \lambda_c^{\,3} \ln 2}{ftc}\left[\frac{1}{2\pi}\int_{\epsilon_0+1}^{\infty} (\epsilon - \epsilon_0)[(\epsilon - \epsilon_0)^2 - 1]^{1/2} I(\epsilon) d\epsilon + \left(\frac{Z}{137}\right)^3 I(\epsilon_0 - 1)\right] \ .$$

In this formula, the ft values (which include the nuclear matrix elements) can simply be taken from the observed lifetimes and decay energies of the decays of the resulting nuclides, such as ^{3}H.

The most appropriate target nucleus has to satisfy the following (rather contradictory) conditions:

(1) It should have allowed or superallowed transitions.

(2) It should have a low threshold energy (such as $^3\mathrm{He} \rightarrow {}^3\mathrm{H}$).

(3) It should have a high proton number Z (such as $^{112}\mathrm{Sn} \rightarrow {}^{112}\mathrm{In}$).

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TABLE I. Events per atom per second with various targets.

Assumed concentration	$\bar{\nu}$ absorption (e^+ production)	K capture ($\bar{\nu}$ induced)
	He → tritium	
1 ppm ^{238}U	0.583×10^{-36}	0.1385×10^{-40}
1 ppm ^{235}U	0.751×10^{-38}	0.5029×10^{-41}
1 ppm ^{232}Th	0.164×10^{-36}	0.614×10^{-40}
1% K	0.83×10^{-36}	0.229×10^{-39}
	^{1}H → neutron	
1 ppm ^{238}U	0.1204×10^{-36}	0.8234×10^{-42}
1 ppm ^{235}U	0	0.3561×10^{-43}
1 ppm ^{232}Th	0.661×10^{-38}	0.182×10^{-42}
1% K	0	0.3779×10^{-41}
	^{112}Sn → ^{112}In	
1 ppm ^{238}U	0.1705×10^{-37}	0.1135×10^{-37}
1 ppm ^{235}U	0	0.4228×10^{-39}
1 ppm ^{232}Th	0.1547×10^{-38}	0.2207×10^{-38}
1% K	0	0.5664×10^{-37}

(4) It should be inexpensive (such as ^{1}H→n).

We performed our calculation for these three nuclides, which show different advantages. The resulting T^{-1} values evidently depend on the actual chemical composition of the earth, which is unknown. This may be the goal of the proposed method: to study the chemical composition of the earth. The resulting T^{-1} numbers (transition probability on one target atom per second) will be given for an average global concentration of 1 ppm ^{238}U, 1 ppm ^{235}U, 1 ppm ^{232}Th, 1% K separately in Table I. The different targets have different sensitivities for the radioactive elements, which offers a distant possibility for the "chemical analysis" of the interior of the earth. The continental crust contains about 0.42 ppm U, 1.68 ppm ^{232}Th, and 0.69% K with ^{40}K isotopic ratio 0.012%. By assuming this, as an example, to be typical for the whole planet (uniform distribution), one arrives at the expected numbers shown in Table II. The resulting numbers are to be compared with the sensitivity of the

TABLE II. Events per atom per second. These numbers are obtained from Table I for each target by adding all contributions from uranium multiplied by 0.42 plus all contributions from thorium times 1.68 plus the contributions of potassium multiplied by 0.69.

Target	^{3}He	^{1}H	^{112}Sn
Global model	1.097×10^{-36}	0.6167×10^{-37}	0.575×10^{-37}

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{A} + e^-$$

reaction, realized by Davis *et al*:

$$T^{-1} \approx 10^{-36}\ \mathrm{sec}^{-1}. \quad (1)$$

Other possible targets of interest give less sensitivity, for instance, ^{209}Bi → Pb gives 0.8×10^{-38} sec^{-1} for the global model and ^{35}Cl → S gives 0.62×10^{-39} sec^{-1}. The method of the detection could be similar in principle to the one pioneered by Davis *et al.*: collecting and counting the radioactive atoms produced by the antineutrino capture, and the mass of the detector would be of the order of several tons as in the experiments of Davis *et al.* This is a serious problem for the targets considered here, but the authors hope that this will seem less discouraging for experimenters in the future than at present. The origin of the planetary system is one of the greatest problems today, and the antineutrino radiation of the Earth contains a piece of information in this respect.

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[1]R. Davis *et al.*, Phys. Rev. Lett. 20, 1205 (1968).

[2]G. Marx, Czech. J. Phys. B 19, 1471 (1969); G. Marx and I. Lux, Acta Phys. Acad. Sci. Hung., 28 (1–3), 63 (1970).