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GEONEUTRINOS AND HYDRIDIC EARTH (OR PRIMORDIALLY HYDROGEN-RICH PLANET)

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Geoneutrino is a new channel of information about geochemical composition of the Earth. We analyzed here the following problem. What statistics do we need to distinguish between predictions of Bulk Silicate Earth (BSE) model and Hydridic Earth (HE) model for Th/U signal ratio? We obtained the simple formula for estimation of error of Th/U signal ratio. Our calculations show that we need more than 22 kt · y exposition for Gran Sasso National Laboratory and Sudbury Neutrino Observatory (SNO). We need more than 27 kt · y exposition for Kamioka site in the case of stopping of all Japanese nuclear power plants.

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INTRODUCTION

Geoneutrino is a new channel of information about geochemical composition of the Earth. Geoneutrino is antineutrino emitted in a decay chain of U, Th and ^{40}K located in the Earth's interior. The first direct measurement of geoneutrino flux was made by the Borexino collaboration [1] and the KamLAND collaboration [2]. Number of events in these detectors depends on the uranium mass in the Earth m(U), the thorium mass in the Earth m(Th) and on their distribution in the Earth. The Bulk Silicate Earth (BSE) model [3] gives $m_{\rm BSE}(\text{U}) = 0.81 \cdot 10^{17}$ kg, $m_{\rm BSE}(\text{Th}) = 3.16 \cdot 10^{17}$ kg, $m_{\rm BSE}(\text{K}) = 0.49 \cdot 10^{21}$ kg. This amount distributes only in crust and upper mantle in the frame of BSE model. Basic idea of BSE model [3] is that the Earth chemical composition must be the same as meteorite chemical composition. The meteorites come mostly from Asteroid Belt (AB). So, the Earth chemical composition must be the same as AB chemical composition.

Chondritic ratio is one of the main characteristics of AB chemical composition and varies from 2.6 to 4.2 [4, 5]. The average value for the Solar System is proposed to be

$$R\left(\frac{\text{Th}}{\text{U}}\right)_{\rm AB} = \frac{m_{\rm Th}}{m_{\rm U}} = 3.9. \tag{1}$$

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The Asteroid Belt is the region of the Solar System located roughly between the orbits of the planets Mars and Jupiter. Some of the debris from collisions can form meteoroids that enter in the Earth's atmosphere. Of the 50,000 meteorites found on the Earth to date, 99.8% are believed to have originated in the Asteroid Belt.

There is the alternative Earth model [7,8], named Hydridic Earth (HE) model, which predicts the primordial chemical elements composition of the Earth. The basic idea of this model is the dependence of planet chemical composition on the distance from the Sun.

V. Larin [7] used the idea that the separation of the chemical elements in the Solar System (chemical differentiation) was originated from the magnetic field of the proto-Sun. He found a correlation between the ratio of the Earth crust chemical element abundances to the Sun chemical element abundances and the first ionization potential of these elements. The observed correlation is theoretically [8] interpreted as the Boltzmann distribution. The numerical model was successfully tested for the observed solar normalized chemical compositions of the Earth, Mars and chondrites.

The 18.3% of the Earth primordial mass is predicted to be hydrogen [8]. The inner Earth would have been and still could be hydrogen-rich. The most part of primordial hydrogen have escaped to atmosphere and space through the degassing of the mantle. The model suggests that large amounts of hydrogen are still located in the core.

On the base of HE model, the work [6] calculated U, Th and ^{40}K abundances in the Earth: $m(\mathrm{U}) = 3.15 \cdot 10^{17}$ kg, $m(\mathrm{Th}) = 5.42 \cdot 10^{17}$ kg, $m(^{40}\mathrm{K}) = 2.63 \cdot 10^{19}$ kg, and obtained Th/U mass ratio for the Earth:

$$R\left(\frac{\mathrm{Th}}{\mathrm{U}}\right)_{\mathrm{HE}} = \left(\frac{m_{\mathrm{Th}}}{m_{\mathrm{U}}}\right)_{\mathrm{HE}} = 1.72. \tag{2}$$

This value is different from chondritic Th/U mass ratio of 3.9 usually used. The accurate measurement of this ratio could permit choosing between BSE model and HE model.

The ability of discrimination between HE and BSE models is limited not only by experimental uncertainty but also by uncertainty of theoretical predictions. The main uncertainty arises from the unknown distribution of Th and U concentrations in the Earth interior. The prediction of Th/U signal ratio is free from this uncertainty.

We analyzed here the following problem. What statistics and what level of background must the geoneutrino detector have for discrimination between predictions of BSE model and HE model?

1. COUNTING RATE OF EVENTS IN GEONEUTRINO DETECTOR

The detector can record the geoneutrino from U and Th decays through the reaction of inverse beta decay:

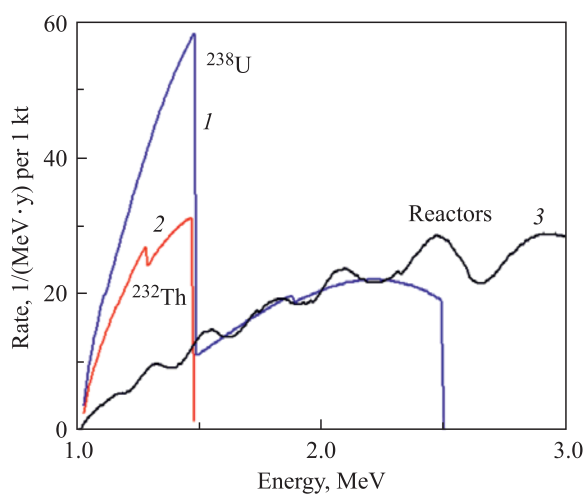
$$\tilde{\nu} + p = e^{+} + n. \tag{3}$$

This reaction has threshold equal to 1.806 MeV.

We calculated for BSE model the counting rate of events in geoneutrino detector from thorium and uranium decays separately and from nuclear reactors as background. The results are shown for 1 kt · y exposition in Table 1 and the Figure for detector consisting of C_nH_{2n} scintillator and locating at Gran Sasso

Table 1. **Number of events for 1 kt · y exposition for Gran Sasso**

$E = 1.5–2.5$ MeV	$E = 1.0–1.5$ MeV
$S_{T,2} = 40$	$S_{T,1} = 29$
$S_{R,2} = 21$	$S_{R,1} = 3$
$S_{\mathrm{U},2} = 19$	$S_{\mathrm{U},1} = 16$
	$S_{\mathrm{Th}} = 10$



Color online. Calculated dependence of counting rate of geoneutrino inverse beta-decay reactions in 1 kt scintillation detector per year versus energy release in the first flash after neutrino reaction in detector. Blue curve (*1*) — geoneutrino from U decay, red curve (*2*) — geoneutrino from Th decay, black curve (*3*) — calculated background from reactors for Gran Sasso location

Table 2. **Number of events for 1 kt · y exposition for Sudbury**

$E = 1.5{-}2.5$ MeV	$E = 1.0{-}1.5$ MeV
$S_{T,2} = 61$	$S_{T,1} = 38$
$S_{R,2} = 37$	$S_{R,1} = 6$
$S_{\mathrm{U},2} = 24$	$S_{\mathrm{U},1} = 20$
	$S_{\mathrm{Th}} = 12$

Table 3. **Number of events for 1 kt · y exposition for KamLAND in the case of stopping of all Japanese nuclear power plants**

$E = 1.5{-}2.5$ MeV	$E = 1.0{-}1.5$ MeV
$S_{T,2} = 27$	$S_{T,1} = 23$
$S_{R,2} = 12$	$S_{R,1} = 2$
$S_{\mathrm{U},2} = 15$	$S_{\mathrm{U},1} = 13$
	$S_{\mathrm{Th}} = 8$

Table 4. **Number of events for 1 kt · y exposition for KamLAND in the case of running of all Japanese nuclear power plants**

$E = 1.5{-}2.5$ MeV	$E = 1.0{-}1.5$ MeV
$S_{T,2} = 189$	$S_{T,1} = 47$
$S_{R,2} = 174$	$S_{R,1} = 26$
$S_{\mathrm{U},2} = 15$	$S_{\mathrm{U},1} = 13$
	$S_{\mathrm{Th}} = 8$

site. In Table 2, the results are shown for the same detector, but locating at Sudbury site, and in Table 3 at KamLAND site. We used the programs written by V. Sinev and results described in [9]. We calculated the number of events of reactor antineutrinos for Kamioka site in the case of stopping of all Japanese nuclear power plants and in the case of running.

In Tables 1–4, we have:

E — energy release in the first flash after neutrino reaction in detector;

$S_{T,2}$ — total number of events in the energy range $E = 1.5{-}2.5$ MeV;

$S_{R,2}$ — number of events from reactors in the energy range $E = 1.5{-}2.5$ MeV;

$S_{\mathrm{U},2}$ — number of geoneutrino events from U decay in the energy range $E = 1.5{-}2.5$ MeV;

$S_{T,1}$ — total number of events in the energy range $E = 1.0{-}1.5$ MeV;

$S_{R,1}$ — number of events from reactors in the energy range $E = 1.0{-}1.5$ MeV;

$S_{\mathrm{U},1}$ — number of geoneutrino events from U decay in the energy range $E = 1.0{-}1.5$ MeV;

S_{Th} — number of geoneutrino events from Th decay in the energy range $E = 1.0{-}1.5$ MeV.

We have from Table 1 for the signal ratio $\left(\dfrac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{BSE}}$:

$$\left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{BSE}} = 0.28. \tag{4}$$

This signal ratio is proportional to R. So, we can calculate this ratio for value (2) $R_{\mathrm{HE}} = 1.72$:

$$\left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{HE}} = 0.28 \cdot \frac{1.72}{3.9} = 0.12. \tag{5}$$

To discriminate the difference between (4) and (5), the experimental accuracy should be better than

$$\delta \frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}(m, t, \eta) < \frac{1}{3}\left(\left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{BSE}} - \left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{HE}}\right), \tag{6}$$

where $\delta \dfrac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}(m, t, \eta)$ — the error of obtained Th/U signal ratio by geoneutrino detector with fiducial mass m and efficiency η during the operational time t.

2. EVALUATION OF Th/U SIGNAL RATIO

Detector measuring antineutrino spectra from geoneutrinos can see the total spectrum generating by uranium and thorium isotopes. But, because of the fact that uranium spectrum extends to higher energies (Figure), we have possibility to separate spectra of uranium and thorium. To do this, we need to measure accurately the high-energy U spectrum part, then to restore the low-energy part of U spectrum, and after to subtract it from the total spectrum.

The procedure of evaluation of S_{Th}, S_{U} values from the experimental data is the following.

$S_{\mathrm{U},2} = S_{T,2} - S_{R,2}$, where $S_{R,2}$ is calculated for the place of detector location. The current accuracy of such calculations is 3%.

$S_{\mathrm{U},2}$ extrapolates to energy region $E = 1.0{-}1.5$ MeV by formula $S_{\mathrm{U},1} = \alpha S_{\mathrm{U},2}$, where α is calculated and depends on U distribution in the Earth due to neutrino oscillations. Here we have from Table 1 $\alpha = 0.85$ and take $\delta\alpha/\alpha = 0.03$.

$S_{\mathrm{Th}} = S_{T,1} - S_{\mathrm{U},1} - S_{R,1}$, where $S_{R,1}$ is calculated for the place of detector location. The current accuracy of such calculations is 3%.

Let us estimate the possible accuracy of measurement of values S_{Th}, S_{U} and $\dfrac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}$, where $S_{\mathrm{U}} = S_{\mathrm{U},1} + S_{\mathrm{U},2}$:

$$\delta S_{\mathrm{Th}} \simeq \sqrt{(\delta S_{T,1})^2 + (\delta S_{\mathrm{U},1})^2} = \sqrt{(\delta S_{T,1})^2 + \alpha^2(\delta S_{\mathrm{U},2})^2}, \tag{7}$$

$$\delta S_{\mathrm{U},2} = \sqrt{(\delta S_{T,2})^2 + (\delta S_{R,2})^2} \simeq \sqrt{S_{T,2}}. \tag{8}$$

We can write from (7) and (8), taking into account that α is near to 1:

$$\delta S_{\mathrm{Th}} \simeq \sqrt{(\delta S_{T,1})^2 + (\delta S_{T,2})^2} = \sqrt{S_{T,1} + S_{T,2}} = \sqrt{S_T}. \tag{9}$$

We obtained the simple formula to estimate the error:

$$\delta\left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right) \simeq \frac{\delta S_{\mathrm{Th}}}{S_{\mathrm{U}}} \simeq \frac{\sqrt{S_T}}{S_{\mathrm{U}}}. \tag{10}$$

3. EXPOSITION

We have from (10) and (6):

$$\delta \frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}(m,t,\eta) \simeq \frac{\sqrt{S_T m t \eta}}{S_{\mathrm{U}} m t \eta} < \frac{1}{3}\left(\left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{BSE}} - \left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{HE}}\right). \tag{11}$$

We can obtain the necessary exposition mt from resolving of (11) in regard to mt:

$$mt > \frac{9 S_T}{\eta S_{\mathrm{U}}^2 \left(\left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{BSE}} - \left(\frac{S_{\mathrm{Th}}}{S_{\mathrm{U}}}\right)_{\mathrm{HE}}\right)^2}. \tag{12}$$

Formula (12) gives us the dependence of necessary exposition on the level of reactors background, because $S_T = S_R + S_{\mathrm{U}} + S_{\mathrm{Th}}$.

Let us substitute to (12) the values S_T, S_{U} from Table 3 for KamLAND laboratory in the case of stopping of all Japanese nuclear power plants and the values (4) and (5):

$$mt > \frac{9 \cdot 50}{0.8 \cdot 28^2 \cdot (0.28 - 0.12)^2} = 27.7\ \mathrm{kt} \cdot \mathrm{y}. \tag{13}$$

We see from (13) that for KamLAND geodetector with feducial mass $m =$ 5 kt about 5.5 years of exposition are necessary to distinguish between (4) and (5) in the case of stopping of all Japanese nuclear power plants.

To demonstrate the influence of background from the nuclear power plants, we substitute to (12) the values S_T, S_U from Table 4 for KamLAND laboratory in the case of running of all Japanese nuclear power plants:

$$mt > \frac{9 \cdot 236}{0.8 \cdot 28^2 \cdot (0.28 - 0.12)^2} = 130.7 \text{ kt} \cdot \text{y}. \tag{14}$$

Let us take from Table 2 for Sudbury laboratory the values for S_T, S_U and the values (4) and (5):

$$mt > \frac{9 \cdot 99}{0.8 \cdot 44^2 \cdot (0.28 - 0.12)^2} = 22.5 \text{ kt} \cdot \text{y}. \tag{15}$$

These calculations show that it is necessary to build the new-generation geoneutrino detector with the fiducial mass not less than 5 kt and with the background from nuclear power plants not too higher than the signal from U geoneutrino.

CONCLUSION

1. We propose to use the Th/U signal ratio $\dfrac{S_\mathrm{Th}}{S_\mathrm{U}}$ to distinguish between predictions of BSE model and HE model.

2. We obtained the simple formula to estimate the error of signal ratio (10): $\delta\left(\dfrac{S_\mathrm{Th}}{S_\mathrm{U}}\right) \simeq \dfrac{\sqrt{S_T}}{S_\mathrm{U}}$.

3. We calculated the signals S_Th and S_U for Gran Sasso National Laboratory site, Sudbury Neutrino Observatory site and for Kamioka site (Tables 1–3).

4. We calculated the signals from the nuclear power plants $S_{R,1}$ and $S_{R,2}$ for Gran Sasso National Laboratory site, Sudbury Neutrino Observatory site and for Kamioka site (Tables 1–3).

5. We obtained that for Gran Sasso National Laboratory site, Sudbury Neutrino Observatory site the exposition not less than 22 kt · y is necessary to distinguish between predictions of BSE model and HE model (12), (13).

6. We obtained that for Kamioka site the exposition 27.7 kt · y is necessary to distinguish between predictions of BSE model and HE model (14) in the case of stopping of all Japanese nuclear power plants.

7. Our calculations show that it is necessary to build the new-generation geoneutrino detector with the fiducial mass not less than 5 kt and with the background from nuclear power plants not too higher than the signal from U geoneutrino.

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REFERENCES

1. *Bellini G. et al. (Borexino Collab.).* Measurement of Geoneutrinos from 1353 Days of Borexino // Phys. Lett. B. 2013. V. 722. P. 295–300; arXiv:1303.2571v2[hep-ex].
2. *Gando A. et al. (The KamLAND Collab.).* Reactor On-Off Antineutrino Measurement with KamLAND // Phys. Rev. D. 2013. V. 88. P. 033001; arXiv:1303.4667v2 [hep-ex].
3. *Mantovani F. et al.* Antineutrino from Earth: A Reference Model and Its Uncertainties // Phys. Rev. D. 2004. V. 69. P. 013001; arXiv:hep-ph/0309013v2.
4. *Lovering J. F., Morgan J. W.* Uranium and Thorium Abundances in Stony Meteorites: 1. The Chondritic Meteorites // J. Geophys. Res. 1979. V. 69, Iss. 10. P. 1964.
5. *Kazunori Shinotsuka, Hiroshi Hidaka, Mitsuru Ebihara.* Detailed Abundances of Rare Earth Elements, Thorium and Uranium in Chondritic Meteorites: An ICP-MS Study // Meteoritics. 1995. V. 30, Iss. 6. P. 694.
6. *Bezrukov L.* Geoneutrino and Hydridic Earth Mode. Version 2. Preprint INR 1378/2014. M., 2014; arXiv:1308.4163[astro-ph.EP].
7. *Larin V. N.* Hydridic Earth: The New Geology of Our Primordially Hydrogen-Rich Planet / Ed. C. Warren Hunt. Calgary, Alberta, Canada: Polar Publ., 1993. 247 p.
8. *Toulhoat H. et al.* Chemical Differentiation of Planets: A Core Issue. arXiv: 1208.2909[astro-ph.EP].
9. *Sinev V. V.* Geoneutrino and the Earth Inner Parts Structure. Preprint INR 1257/2010. M., 2010. 16 p. (in Russian); arXiv:1007.2526v1[hep-ph].