Geoneutrino : experimental status and perspectives

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Abstract. The current results of the Borexino and KamLAND on geoneutrino are presented and the perspectives for measurement of geoneutrino fluxes both on existing and planned detectors are discussed. We discuss also the nuclear physics inputs relevant for precision measurement of the geoneutrino fluxes.

1. Introduction
Geoneutrino is an electron antineutrino accompanying $\beta$-decay of nuclear long-lived isotopes present in the Earth. The natural radioactivity of the Earth is a powerful source of heat, influencing the thermal history of the Earth. Radiogenic heat and primordial heat of the Earth constitutes two main contributions to the total energy loss of the Earth. Radiogenic heating helps power plate tectonics, hot-spot volcanism, earthquakes and mantle convection. Analysis of the available measurements of temperature gradients in mines gives the total thermal production of $47 \pm 2$ TW [1].

Geoneutrino flux measurements do provide experimental evidence for the quantity and distribution of radioactive elements internally heating the Earth, as the direct measurement of the composition of basic regions is possible for the Earth’s crust only. Information on the extent and location of this heating better defines the thermal dynamics and chemical composition of Earth.

2. Models
Model predicting abundances of radioactive elements in each part of the Earth is required to calculate the geoneutrino signal. The description of the modern crust+mantle system is provided by a model of Bulk Silicate Earth (BSE), which represents a reconstruction of a primitive primordial mantle of the Earth on the base of geochemical arguments. The primitive mantle is the mantle formed immediately after the separation of the core before the crust differentiation. The composition of the primitive mantle is derived from the composition of the chondritic meteorites, which is practically identical to the chemical composition of the Sun, excepting the lightest elements, such as hydrogen and helium.

The homogeneous composition of seismically differentiated regions is usually assumed in model. The abundances of U/Th in the internal regions is based on the composition of corresponding meteorites in assumption of typical composition of the Earth within the frames of the Solar system. The BSE model provides full amount of U, Th and K in the Earth as these lithophile elements (having affinity to the silicate minerals and melts) should not
be present in the Earth's core. The BSE model is in a good agreement with the majority of experimental observations concerning the core and upper mantle. BSE models can be classified in accordance with predicted radiogenic heat, that depends on the initial assumptions. Depending on underlying assumptions three classes of the models are considered: cosmochemical, geochemical and geodynamical ones (see [2] for more details), predicting radiogenic thermal flux of $11\pm2$, $20\pm4$ and $33\pm3$ TW correspondingly.

As the prediction for the crust contribution is bounded stronger compared to the mantle contribution, the models in fact differs even more significantly on predicted mantle contribution: low Q ($3\pm2$) for cosmochemical, medium Q ($12\pm4$) for geological and high Q ($25\pm3$) for geodynamical models.

Antineutrino spectra expected from $^{238}$U and $^{232}$Th chain, as well as from $^{40}$K, are presented in fig.1 (left). A fraction of antineutrino spectra from $^{238}$U and $^{232}$Th chains exceeds the threshold of the inverse beta-decay on proton. This makes their detection by liquid organic scintillator (LOS) detectors in the inverse beta decay (IBD) reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (having a threshold of 1.8 MeV). An ideal geoneutrino signal in IBD detector is the product of the geoneutrino energy spectrum and corresponding cross section of the IBD reaction, for real-world detector signal will be smeared by resolution.

The theoretical (for ideal detector with infinite resolution) IBD spectra from U and Th chains in assumption of the secular equilibrium in the chains and at the chondritic ratio of Th/U masses $M(\text{Th})/M(\text{U})=3.9$ are shown in fig. 1 (right). The visible difference in the spectra makes contributions from U and Th potentially distinguishable, though the low-energy part of the U spectrum has a noticeable contribution very similar to the Th spectrum, weakening the discrimination power of the U and Th signals.

3. Detectors and backgrounds.
At present only two collaboration presented results on the geoneutrino observation: KamLAND and Borexino. Both collaborations are using detectors on the base of the LOS. Principal backgrounds in the geoneutrino search with IBD detectors are: reactor antineutrinos, cosmic muons induced backgrounds, including cosmogenic production of $(\beta n)$- decaying isotopes and internal radioactive contamination.

**Reactor antineutrinos.** For KamLAND measurements they contributed 81% of the total antineutrino signal geoneutrino window of [0.9-2.6 MeV] in the initial stage of the experiment, for the Borexino the reactor contribution is 36%. After the Fukushima disaster all Japan's nuclear
plants were closed, the last one went offline for maintenance on May 5, 2012. Correspondingly, the reactor background has significantly reduced at the KamLAND site.

**Cosmic muons induced backgrounds**, including cosmogenic production of $(\beta n)$-decaying isotopes. At LNGS the muons flux is of about factor 7 lower than at the Kamioka site. In the analysis a veto of 2 seconds is applied after each muon passing through the detector to remove events caused by short-lived cosmogenic isotopes decaying through $(\beta n)$ channel. In KamLAND data analysis an additional condition on muons is applied: removed muon should generate a shower, this reduce live time losses to the moderate 4% compared to 10% of the live-time loss in Borexino analysis, despite of the lower muon flux in the Gran Sasso site. The suppression of background from the fast neutrons from buffer is achieved by applying a shorter 2 ms veto (this background is mainly caused by multiple neutron production).

**Internal radioactive contamination**: contributes through accidental coincidences and $(\alpha n)$-reaction on $^{13}$C, monoenergetic $\alpha$ with kinetic energy of 5.3 MeV are produced in $^{210}$Po decays. The both backgrounds are much lower in the Borexino because of typical contamination of 3-4 orders of magnitude lower; later KamLAND reported factor 20 on $(\alpha n)$ reduction.

4. Measurements

The first indication of the non-zero geoneutrino signal was reported by KamLAND in 2005 [5]. In April 2010 the first high significance confirmation on the geoneutrino signal come from Borexino [8], the collaboration reported the observation of the geoneutrino signal at the 99.997% level.

The actual results are summarized in Table 1. The last up-to-date measurement was released by Borexino in 2015, the KamLAND analysis of the most interesting period of the data taking with reduced reactor background was presented at the “Neutrino Research and Thermal Evolution of the Earth” conference at the end of 2016.

The latest Borexino geoneutrino flux measurement was performed with 2056 days data set, the expected ratio of geoneutrinos to antineutrinos from the European reactors is about 1:2. Backgrounds from other sources for antineutrino measurement in Borexino are negligible and do not exceed one event for the measurement time. The observed geoneutrino signal is evaluated by fitting the experimental spectrum with the spectral contributions from geoneutrino (with chondritic Th/U mass ratio fixed at $M(\text{Th})/M(\text{U})=3.9$), reactor neutrino and residual backgrounds. The observed geoneutrino flux is totally consistent with the expected one for most of geophysical models. The probability of the absence of geoneutrino signal is negligible, namely, $3.6 \times 10^{-9}$ (5.9$\sigma$). Moreover, for the first time in the history of geoneutrino observations, the non-zero contribution from the mantle is confirmed at 98% C.L.

The latest results of KamLAND are obtained including ~3.5 years of data with the low reactor background, the evidence of the geoneutrino signal achieves 7.9$\sigma$. For the first time it is reported the positive indication of the U signal (at 3.44$\sigma$ C.L.) with free U/Th ratio, and the “global” U/Th ratio measurement of $M(\text{Th})/M(\text{U})=4.1^{+5.3}_{-3.3}$ (with upper limit of 17.0 for the masses ratio of Th/U at 90% C.L.). All the values are consistent with chondrite data and the BSE models.

5. Near future

The Borexino detector will accumulate about 3 additional years of data in solar mode before the start of the SOX program. Further improvement of result is expected due to the tuning of the muon veto cut and applying the analysis to the whole volume of the detector.

The collaboration plans to improve the performance of cuts following KamLAND approach, this should save about 9% of live-time. Even stronger gain in statistics up to another 50% is possible if including all the data in the analysis without applying fiducial volume cut, this needs better understanding of the external backgrounds observed close to the IV walls.
KamLAND is continuing the data taking with Japanese nuclear reactors switched off, detecting about 14 geoneutrino events per year.

SNO+ detector should start the data taking soon. It is located at deep Sudbury mine, at 6010 m.w.e., and operates 780 tonnes LAB- based LOS detector. 29 geoneutrino events per live-year are expected compared with 26 events from reactors in the same energy range.

Multitonne detectors of the third generation reactor experiments (JUNO [14]) will be sensitive to geoneutrino. The expected geoneutrino signal is 39.7 ± 7.3 TNU [16], JUNO will acquire about 400 geoneutrino events per year. Signal from the reactors in the geoneutrino energy window will contribute 354 ± 45 TNU, making difficult the extraction of the geoneutrino signal. Nevertheless, 10% precision can be achieved with 3 years of the data taking, if the precision reactor spectrum description will be provided. The same set of data will allow to obtain the contribution of U with 20% precision and of Th with 30% precision [14].

Geoneutrino studies are planned at the China Jinping Underground Laboratory (CJPL), which is located at 2400 m depth under the Jinping Mountain in Sichuan, China. Predicted geoneutrino signal is 59.4 ± 6.8 TNU with expected background from nuclear reactors of only 6.7 ± 0.1 TNU in the geoneutrino energy range of interest [1.8, 3.3] MeV [10]. The Jinping Neutrino Experiment collaboration plans to build two detectors in the experimental hall of CJPL, using LOS or slow LS. The design mass of each of two detectors is 1.5 kt [11].

Another possible site for geoneutrino exploration is Baksan laboratory in Russia, 10 kt LOS detector is being discussed [12]. Expected geoneutrino signal is 52.6 TNU with expected background from nuclear reactors of only 14.4 TNU in the energy range of interest.

LENA was a project of 50 kt deep underground multipurpose LOS detector [13], at the moment there is no financial support of the project. About 1500 geoneutrino events per year were expected. Another project without financial support is Hanohano, which should be a portable 10 kt LOS device deployed from the barge. It would be aimed to extract mantle contribution in the total geoneutrino signal. About 100 geoneutrino events per year are expected.

In the absence of a “direct” measurement of the mantle signal with underwater detector, the only possible way to extract the mantle signal and discriminate the geophysical models would be the joint analysis of the geoneutrino data from different locations together with better understanding of the local contribution from the crust.

### 6. Nuclear physics uncertainties of the expected geoneutrino signal in IBD antineutrino detector

Only two isotopes in each of $^{238}\text{U}$ and $^{232}\text{Th}$ chains have enough energetic $\beta$-decays to provide a contribution to the IBD signal. In the $^{232}\text{Th}$ decay chain these are two branches of $^{228}\text{Ac}$ decay (into ground state and to the first excited one), and decay of $^{212}\text{Bi}$ into the ground state. In the $^{238}\text{U}$ chain these are the decays of $^{234m}\text{Pa}$ and 4 branches of the $^{214}\text{Bi}$ decay. The properties of $\beta$-decays in the $^{232}\text{Th}$ and $^{238}\text{U}$ chains contributing to geoneutrino signal are presented in

| Experiment/year | Live-time, days | Exposure, t-yr | number of candidates | number of geo-$\nu$ | Total geo-$\nu$ signal, TNU | Mantle geo-$\nu$ signal, TNU |
|-----------------|-----------------|----------------|---------------------|-------------------|-----------------------------|-----------------------------|
| KL/2013 [6]     | 2991            | 5780 ± 118    | –                   | 116 ± 25          | 30.9 ± 7.3                  | –                           |
| KL/2016 [7]     | 3901            | 7537          | 1130                | 164 ± 25          | 35.4 ± 5.4                  | 8.8 ± 6.4                   |
| Bx/2015 [9]     | 2056            | 907±44        | 77                  | 23.7 ± 5.7        | 43.5 ±10.7                  | 20.9 ±10.3                  |

Table 1. Borexino and KamLAND results on the geoneutrino flux measurement. Results presented by KL in 2016 [7] still have preliminary status. 1 TNU, Terrestrial Neutrino Unit, corresponds to 1 event per year for $10^{32}$ protons in target (this corresponds to roughly 1 kton of typical LOS. Thus, a count in TNU units roughly corresponds to the expected event rate per year in 1 kton scale IBD detector.
Table 2. Properties of β-decays in the 232-Th chain contributing to geoneutrino signal in IBD detectors. The second column contains activity of the corresponding reaction with respect to the activity of parent 232-Th. The $I \pm \delta I$ column contains the relative intensity of the corresponding decay (with respect to one parent decay) with associated experimental error. $Q$ is the β-decay end-point. $S$ is signal measured in TNU in assumption of $10^6 \text{cm}^{-2}\text{s}^{-1}$ total neutrino flux (from 238-U and 232-Th chains only) distributed between U and Th in accordance to the chondritic ratio and in assumption of the universal (allowed) shape; alternative values (separated by a slash) are calculated using shape factor corresponding to the decay type. $f_{\text{Th}}$ and $f_{\text{tot}}$ denote the fraction of the signal in the 232-Th chain and in total geoneutrino signal correspondingly in assumption of the allowed shapes. When calculating the values in the last column, the chondritic ratio of 3.9 for Th/U masses was assumed.

Table 3. Properties of β-decays in 238-U chain contributing to geoneutrino signal in IBD detectors. The notations are the same of Table 2.

Tables 2 and 3, respectively.

As one can see from Table 2, the contribution from 228-Ac is quite uncertain. It is contributing 0.6% in the total antineutrino signal uncertainty, because of the poorly measured relative intensity of the decay. Decay of 214-Bi into the ground state contributes another 0.4% into the total error of the signal. Summed quadratically, these two contributions constitute 0.7%, and other transitions in both decay chains do not contribute significantly to the total signal uncertainty. The uncertainty of the β-decay shape can, in principle, contribute much more to the signal uncertainty. The values after slashes in the $S$ column of the tables are calculated in assumption of the allowed shape in accordance with decay type (mostly first forbidden) and can serve as an estimation of (maximum) systematics associated with unknown precise shapes of the decay. One can see that these errors can contribute up to 10% into the signal. These errors cannot be summed quadratically because of the unknown correlations; all can contribute in the same direction. Any deviation from the allowed shape towards the forbidden one will increase the total signal. There are good qualitative reasons to assume the allowed shape for these β-decays, as discussed in [18]. At any rate, the quantitative estimation of the corresponding errors is quite complicated. It is clear that only precise experiments can provide proper shapes. The most important fraction of β-spectra to be investigated, from the point of view of geoneutrino signal calculations, lays in its low-energy region, the most difficult region to access in experimental studies (because of the detector threshold and increase of backgrounds at low energies).

An attempt to measure the shape of the 214-Bi $\beta + \gamma$ decay was reported in [17]. The feeding probability of the lowest state of 214-Bi, providing the most important contribution for geoneutrino signal, was found to be $p_0 = 0.177 \pm 0.004$ under the assumption of universal
neutrino spectrum shape, consistent with the indirect estimate of the table of isotopes\(^1\). Larger statistics and reduction of systematics should allow for the testing of possible distortions of the neutrino spectrum from that predicted using the universal shape [17]. It was found that the effect of uncertainties on the geoneutrino signal is mostly negligible: in the fit of the \(^{214}\)Bi decay data with the completely unconstrained shape parameter, \(p_0\) and \(p_1\) (feeding probabilities to the ground and the first excited states, the only one giving a contribution above 1.81 MeV) the effects of changes of shape and of \(p_0\) on the signal are anticorrelated, if the spectrum is deformed such that there are more (less) low-energy electrons, the corresponding best-fit value for \(p_0\) is lower (higher). While the values of \(p_0\) range from 0.13 to 0.20, the signal changed only by about \(\pm 2\%\), i.e. the resulting signal depends weakly on the spectral shape [17].

7. Conclusions
Geoneutrino existence is confirmed independently by Borexino and KamLAND. The precision of both available measurements is still too low: \(\simeq 28\%\) and 17% correspondingly for the U+Th signal using chondritic mass ratio. Different geological models for the moment can’t be discriminated by existing measurements, more precise measurements are needed. Regional measurements at location of experiments are needed to provide more precision for the models. Independent measurements at various sites are highly desirable to check contributions from crust/mantle. For the future precision measurements one should provide corresponding precise nuclear data concerning probabilities of the transition and the shapes of the beta-decay contributing to the geoneutrino signal.

References
[1] Davies J H, Davies D R 2010 Earth’s surface heat flux Solid Earth 115
[2] Šrámek O et al. 2013 Geophysical and geochemical constraints on geoneutrino fluxes from Earth's mantle Earth and Planetary Science Lett. 361 356
[3] Eguchi K, et al (KamLAND Collaboration) 2003 First results from KamLAND: evidence for reactor antineutrino disappearance Phys. Rev. Lett. 90, 021802
[4] Alimonti G, et al. (Borexino Collaboration) 2009 The Borexino detector at the Laboratori Nazionali del Gran Sasso. NIM A 600, 568
[5] Araki T, et al. (KamLAND collaboration) 2009 Experimental investigation of geologically produced antineutrinos with KamLAND Nature 436 499
[6] Gando A, et al. 2013 Reactor on-off antineutrino measurement with KamLAND Phys. Rev. D 88 033001
[7] Watanabe H 2016 talk at the “Neutrino Research and Thermal Evolution of the Earth”
[8] Bellini G, et al. (Borexino collaboration) 2010 Phys. Lett. B 687, 299
[9] Agostini M, et al. (Borexino Collaboration) 2015 Spectroscopy of geo-neutrinos from 2056 days of Borexino data Phys. Rev. D 92 031101
[10] Wan L, et al. 2017 Geoneutrinos at Jinping: Flux prediction and oscillation analysis Phys.Rev.D 95 053001
[11] Beacom J F, et al. 2016 Letter of intent: Jinping Neutrino Experiment arXiv:1602.01733
[12] Barabanov I R, et al. 2017 Large-Volume Detector at the Baksan Neutrino Observatory for Studies of Natural Neutrino Fluxes for Purposes of Geo- and Astrophysics Physics of Atomic Nuclei 80(3) 446
[13] Wurm M, et al. (LENA Collaboration) 2011 The next-generation liquid-scintillator neutrino observatory LENA arXiv:1104.5620
[14] An F, et al. (JUNO Collaboration) 2016 Neutrino Physics with JUNO J. Phys. G 43 030401
[15] Learned J G, Dye S T and Pakvasa S 2008 Hanohano: A Deep Ocean Anti-Neutrino Detector for Unique Neutrino Physics and Geophysics Studies arXiv:0810.4975
[16] Strati V et al. 2015 Expected geoneutrino signal at JUNO Progress in Earth and Planetary Science 2, 5
[17] Fiorentini G et al. 2010 Nuclear physics for geo-neutrino studies Phys.Rev.C 81 034602
[18] Fiorentini G, Lissia M and Mantovani F 2007 Geoneutrinos and Earth Interior Phys.Reports 453 117
[19] Alkovali Y A, 1995 Nuclear Data Sheets for A=214 Nucl. Data Sheets 76, 127
[20] ENSDF: Evaluated Nuclear Structure Data File Search and Retrieval https://www-nds.iaea.org/ensdf

\(^1\) the consistency was checked against the value \(p_0 = 0.182 \pm 0.006\) from [19], updated data [20] gives \(p_0 = 0.1910 \pm 0.0017\) that is 3.2\(\sigma\) away from the measured. This could indeed indicate the deviations from the allowed universal shape.