Geoneutrino observation

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Neutrinos from the Earth's interior "geoneutrinos" have been observed to reveal Earth's composition, heat budget, and the origin of the Earth. Observations by KamLAND and Borexino experiments for 15 years are reviewed.

Keywords: Neutrino; Geoneutrino

1. Geoneutrino

Recent progress on the research about "why and how the sun and the stars shine" is quite notable, which has been summarized in this parallel session. Here I would like to review neutrinos from another familiar celestial body, the Earth. Neutrinos from the Earth ("geoneutrinos") are low-energy electron antineutrinos ($\bar{\nu}_e$) emitted in the decay chains of uranium (U), thorium (Th), and potassium (K) in the Earth's interior. Geoneutrino is expected as a probe of Earth's chemical composition. Also the decay of those radioactive elements contributes to the Earth's heat production. Then geoneutrino is a tool to reveal the Earth's energy budget. Although the existence of geoneutrino is predicted more than 50 years ago[1–3] experimental research has been difficult. Since Borexino and KamLAND experiments were planned, they have been hoped as the first experimental research of geoneutrinos.

With those liquid scintillator detectors, geoneutrinos (geo-$\bar{\nu}_e$'s) are detected via "inverse β decay" mode: $\bar{\nu}_e + p \rightarrow e^+ + n$. Considering the difference of masses of neutron (m_n) and proton (m_p), $m_n - m_p = 1.3$ MeV, the mass of positron ($m_e = 0.5$ MeV), and neglecting the small neutron recoil, the threshold of this reaction is $E_{th} \simeq m_n - m_p + m_e = 1.8$ MeV, above which neutrino energy E_ν and positron energy E_{e^+} (the kinetic energy of the positron plus the electron-positron annihilation energy) are related as $E_\nu \simeq E_{e^+} + E_{th} - 2m_e = E_{e^+} + 0.8$ MeV. The potassium neutrino is below E_{th}, so liquid scintillator detectors observe only uranium and thorium neutrinos. With energy spectrum (E_{e^+} spectrum which reflects E_ν spectrum), uranium (U) and thorium (Th) neutrinos can be separately measured. To obtain total geoneutrino flux with less statistical uncertainty, the relative abundance of U and Th is sometimes assumed to be Th/U = 3.9, based on geological consideration.

As Borexino and KamLAND plans started, calculation of expected flux of geoneutrinos, and expected signals of these detectors have also been performed. One of the examples is Ref. 4, in which expected "peaks" of geoneutrinos around $E_{e^+} \simeq 1$ to 3 MeV are shown. Also shown are the expected background spectra of nuclear reactor $\bar{\nu}_e$, showing that reactor $\bar{\nu}_e$ of Borexino is much less than that of KamLAND.

2. Experimental Research

In 2005, the first experimental research of geoneutrinos has been done,[5] in which KamLAND measured low-energy spectrum of $\bar{\nu}_e$ and fitted it to geoneutrino, reactor neutrino and other background spectra. As shown in Fig. 1, geoneutirno contribution is indicated although the statistical power is limited.

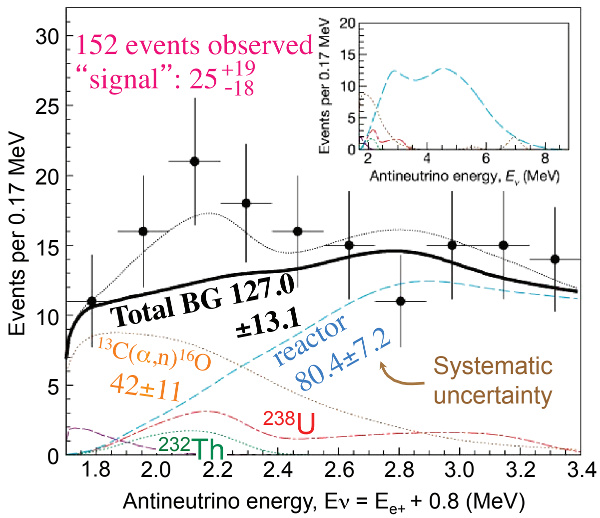

Fig. 1. First experimental research of geoneutrinos. Points are data, lines with labels and numbers are estimated background (thin line around 1.8 MeV is random coincidence). Lines labeled as ^{238}U and ^{232}Th are best-fit geoneutrino signals. Thick black line is the estimated total background, and thin black line is that with the best-fit signals added.

In 2010, Borexino collaboration reported their first result of geoneutrino observation,[6] with which the observation with two detectors on the Earth started. Borexino is an ultra pure detector and reactor neutrino flux is much less than KamLAND site. Thanks to those low background environment, the existence of geoneutrino was confirmed at 4.2 σ confidence level.

In an updated result of KamLAND,[7] it has been shown that the radiogenic heat source inferred from geoneutrino flux is significantly less than the total heat flow from the Earth's interior. With this result they concluded that there is contribution of secular cooling of the Earth to the total heat source of the Earth.

In the updated result of Borexino[8] released in 2013, the signal of geoneutrino became clearer and the probability for null geoneutrino measurement was shown to be 6×10^{-6}. The latest data of KamLAND was also shown[9] in 2013, which included the data of the period with most of Japanese nuclear reactors off. With these data, low background observation of geoneutrino was done also with KamLAND. The reactor $\bar{\nu}_e$ background was also unambiguously estimated using reactor on and off data. In those reports in 2013,[8,9] existence of mantle geoneutrino contribution was indicated by using both data in a cooperating way because crust contributions are different between KamLAND and Borexino sites.

In 2015, Borexino collaboration released new result[10] and reported that the probability for null geoneutrino measurement is 3.6×10^{-9} corresponding to 5.9 σ confidence level. This should be a conclusive result for geoneutrino existence. The latest result of Borexino was shonw in Ref. 11. This comprehensive report includes all the aspects of geoneutrino research, i.e., physics, geology, experiment, and data analysis of geoneutrino. All the researchers involved in geoneutrino study are recommended to read it carefully so that they are stimulated for new research. Also in this report, multiple Earth models are carefully tested with their latest data, including cosmochemical, geochemical, and geodynamical models.

3. Research in Geology and Theory

With those experimental data, research in geology and theory also became active. Combined analysis of KamLAND and Borexino data has been done by theorists. Ref. 12 is one of combined analysis, in which common and independent uncertainties of KamLAND and Borexino are treated properly and carefully with considering correlation.

New calculations of geoneutrino flux have also been done using up-to-date data and more precise and refined method of calculation. For example, such up-to-date "reference models" are reviewed in Refs. 11–13.

4. Future Experiments

Although the observation with two detectors has lasted for more than 10 years, new detectors will be ready and expected to start their observations. SNO+[14] is a large liquid scintillator detector in Canada to search for neutrinoless double beta decay. It can also observe geoneutrinos. Large flux of geoneutrino is expected from the continent crust. In April 2021, SNO+ completed liquid scintillator filling. We have to stay tuned.

JUNO[15] is a multipurpose neutrino detector planned to be constructed in China. Their main purpose is to measure reactor neutrino oscillation to further improve Daya Bay achievements. When completed it will be the largest liquid scintillator detector (20 kton) in the world. The construction already started.

Jinping Neutrino Experiment[16] is planned in China. When completed, it will be the deepest detector in the world, with 2400 m overburden of rocks. It aims at observing large flux of geoneutrinos from Himalaya, which is a part of one of the largest continental crust of the present-day Earth.

For more research, especially for mantle geoneutrino detection, large liquid scintillator in the deep ocean[17] is one possibility. Directional measurement of electron antineutrinos is another future possibility in order to get more information about geoneutrino source distribution. Although the directional measurement was done by Chooz experiment,[18] application for large detector is not easy and under development. Considering the observation at a lot of points are essentially important, design of cheap detector[19] may be useful to construct as many detector as possible.

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