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JUNO Sensitivity to geoneutrinos

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Summary. — Geoneutrinos are neutrinos generated from the decay of natural radioactive elements in the Earth. From these decays, the ratio between the number of neutrinos and the energy released (radiogenic heat) is well known. In order to understand the different processes of the Earth, Bulk Silicate Earth models are formulated, providing expected abundances of radioactive elements and radiogenic heat. Therefore, by measuring geoneutrinos, the different BSE models can be tested. Additionally, the total amount of heat released from the surface of the Earth is coupled with the different dynamical processes. The total heat budget is composed of the cooling from the Earth's formation and the radiogenic heat. Thus, geoneutrinos also give insight into dynamical processes. The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton Liquid Scintillator detector that will be able to measure geoneutrinos with high precision thanks to its great volume. It is expected to achieve 10% precision in just 6 years, improving upon current results from Borexino and KamLAND.

1. – Geoneutrinos

The Earth is composed of, basically, three main layers: Crust, Mantle, and Core. The Crust is the uppermost layer, which can be studied via direct methods such as rock samples. Deeper layers, like the Mantle, can only be studied by seismology, but it does not provide any chemical composition information. In some cases, rock samples from the upper Mantle could be dragged to the surface through tectonic or volcanic activities, but during transportation, the sample might be altered, rendering the sample unreliable. Therefore, new methods must be developed in order to study the deeper parts of the Earth.

A correlation between the isotopical ratios of the solar photosphere and the C1 chondrite meteorites was observed [1]. Since the Earth was also formed with the same materials, it might be possible to also assume the same isotopic ratios in the primordial Earth. In order to answer this type of question, the Bulk Silicate Earth (BSE) models are formulated. These models provide the expected element abundances and *radiogenic heat* emitted by the Earth.

The total heat budget of the Earth is divided between the primordial heat, coming from the cooling of the Earth's formation, and the radiogenic heat, generated by the decay of the natural radioactive elements in the Earth known as Heat Producing Elements (HPE). By measuring the radiogeninc heat, any proposed dynamical processes are constrained by the remaining of the total heat budget.

Geoneutrinos are (anti)neutrinos that are produced in the decay of HPEs. From nuclear physics, the ratio between the number of neutrinos and the amount of energy released is very well known [2]:

$$
\begin{aligned}
{}^{238}\mathrm{U} &\rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}, \\
{}^{235}\mathrm{U} &\rightarrow {}^{207}\mathrm{Pb} + 8\alpha + 4e^- + 4\bar{\nu}_e + 46.4\ \mathrm{MeV}, \\
{}^{232}\mathrm{Th} &\rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.8\ \mathrm{MeV}, \\
{}^{40}\mathrm{K} &\rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.32\ \mathrm{MeV}.
\end{aligned}
\tag{1}
$$

Thus, by measuring the geoneutrino flux, the radiogenic heat can also be constrained. Additionally, through geoneutrinos, different BSE models can be tested, since different assumptions on the distribution and abundances of the HPEs will lead to different geoneutrino fluxes.

2. – Existing measurements

Geoneutrinos have been measured by two different experiments: Borexino and KamLAND.

2·1. *Borexino.* – Borexino experiment is located in Gran Sasso, Italy [3]. Based at the *Laboratori Nazionali del Gran Sasso* at a depth of 3800 w.m.e, Borexino was composed of a detector with 0.3 kton of Liquid Scintillator (LS) and achieved a very low radioactive background. Its main objective was the detection of solar neutrinos. Using almost 10 years of data, it was able to measure $52.6^{+9.4}_{-8.6}(\mathrm{stat})^{+2.4}_{-2.1}(\mathrm{sys})$ geoneutrino events at 18% precision, assuming a fixed ratio of U and Th masses to be the same as the one observed in the C1 chondrites.

2·2. *KamLAND.* – The Kamioka Liquid Scintillator Antineutrino Detector (KamLAND) [4] is an experiment located in the Kamioka mine, Japan. The main objective of the experiment was to measure neutrino oscillations at a long baseline ($\sim$200 km from the nuclear power plant). By assuming the fixed U and Th mass ratio of the C1 chondrites, it was able to observe 183^{+29}_{-28} geoneutrinos events, resulting in $\sim$15% precision with around 18 years of data [5].

3. – JUNO experiment

The Jiangmen Underground Neutrino Observatory is located in the Jiangmen region, south China [6]. It is a LS detector designed to be the biggest of its kind to date. The central detector has a diameter of 35.4 m and holds 20 kton of LS. It is placed underground at 650 m of depth in order to reduce the incoming cosmic background. Its main objective is the determination of the Neutrino Mass Ordering (NMO) and a precise measurement of the neutrino oscillation parameters. For this, it aims to reach 3% of energy resolution at 1 MeV. The distance to the two nearest nuclear power plants is 52.5 km, optimized for the determination of NMO.

4. – JUNO sensitivity to geoneutrinos

In JUNO, MeV-scale neutrinos are detected via the inverse beta decay (IBD). The antineutrino interacts with a proton in the LS, producing a positron and a neutron pair. The positron anihilates quickly, creating the prompt signal, while the neutron thermalizes and is then captured after $\sim$200 μs, creating the delayed signal. By searching for the coincidence of these two events, the background can be reduced significantly. This channel has an energy threshold of 1.8 MeV; therefore, only geoneutrinos from ^{238}U and ^{232}Th, having higher energies, can be detected.

Thanks to its large volume, JUNO is expected to contribute to several topics, geoneutrinos being one of them. It is expected to measure more geoneutrinos than KamLAND and Borexino in just 1 year, providing the most statistically significant measurement. In table I, the expected backgrounds and their rate per day are shown. Additionally, in fig. 1, an example of the expected signal for 10 years of data taking is presented. It can be clearly seen that reactor anitneutrinos will be the most dominant background. Nonetheless, JUNO will be able to reach around 10% precision after 6 years of data taking, assuming the fixed U and Th mass ratio from C1 chondrites ($M_{\mathrm{Th}}/M_{\mathrm{U}} = 3.9$). Here, all non-reactor backgrounds are constrained by independent data, with reactor neutrinos being the only unconstrained component above the end point of geoneutrinos. Oscillation parameters are free in the fit, and shape uncertainties are also considered. Under these same fit conditions, JUNO will be able to provide independent measurements of U, Th, and their sum with $\sim$35%, $\sim$30%, and $\sim$15% precision after 10 years of data taking.

Table I. – *Signal and background inputs are considered in the calculation of the sensitivity. In the second column, the rate per day for each component is presented, while the other two columns contain the percentage uncertainty for both rate and shape.*

	Rate [cpd]	Rate unc.	Shape unc.
Geoneutrinos	1.2	-	5%
Reactor Neutrinos	43.2	-	Daya Bay [7]
Accidentals	0.8	1%	-
^{9}Li/^{8}He	0.8	10%	10%
^{13}C(α, n)^{16}O	0.05	50%	50%
Fast Neutrons	0.1	100%	20%
World Reactor	1	5%	5%
Atmospheric	0.16	50%	5%

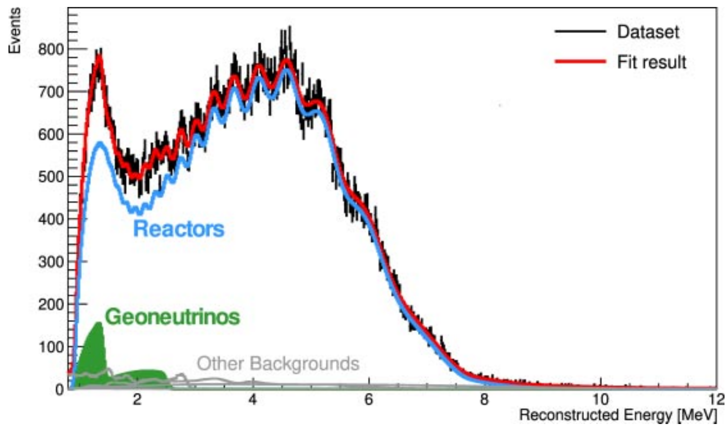

Fig. 1. – Illustration of the expected signal and background at 10 years of exposure. It can be observed that there is a clear dependence on reactor antineutrinos (blue), while the rest are not so dominant.

5. – Conclusion and outlook

Geoneutrinos are an important measurement that can enable a better understanding of the Earth. Its direct relationship with the heat loss from natural decays on the Earth can answer and test the existing geo-models. In order to reach high precision, big experiments are needed. JUNO will be able to provide the third geoneutrino measurement in an independent geographical location. In 1 year, it will surpass the number of geoneutrinos detected by Borexino and KamLAND in their complete data taking period and reach 10% precision on the total flux in 6 years, assuming the mass ratio of U and Th from the C1 chondrite meteorites. Furthermore, independent measurement of U and Th contributions to geoneutrinos will be possible. Lastly, efforts are ongoing on the modeling of the local crust around JUNO, which is vital for the Mantle contribution measurement.

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