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News & Views

Earth Sciences

Bold frontier in Chinese geoscience

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It takes lots of energy to drive plate tectonics, mantle convection, and the geodynamo. Resolving the 150-year-old question posed by Lord Kelvin about the origin and power in the Earth remains an elusive goal. China is taking bold action to address these questions with two new and daring experiments that will measure with high fidelity the Earth's emission of geoneutrino. Neutrinos and their anti-matter counterparts are near massless and uncharged elementary particles that travel at close to the speed of light. Some 10^{25} of these ghost-like particles come zipping out of the Earth every second stealing away heat evolved from the decay of radioactive elements.

Electron antineutrinos $(\bar{\nu}_e)$ are produced during β^- decay of neutron-rich nuclei from natural and anthropogenic (nuclear reactors) sources. Geoneutrinos are those electron antineutrinos emitted from nuclei undergoing β^- decay inside the Earth. Those from Th and U have the highest energies and are detectable by the inverse beta decay method ($\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$; where $\mathrm{p} = \text{proton}$, $\mathrm{e}^+ = \text{positron}$, $\mathrm{n} = \text{neutron}$) with large underground liquid scintillation devices. The Earth is mostly transparent to these elusive messengers that virtually escape detection, but by measuring a minuscule fraction of this flux, we determine the abundance and distribution of heat sources inside the Earth [1].

China is now entering the frontier of Neutrino Science and is poised to make major advances with the construction of the 20-kiloton Jiangmen Underground Neutrino Observatory (JUNO) in southern Guangdong Province and the proposal to construct the world's deepest, cleanest, and quietest kiloton detector at the China Jinping Laboratory (CJPL) on the eastern slopes of the Himalayas. Neutrinos are a hot topic, and in June at Tsinghua University, a band of scientists responded to the recommendation of the CJPL International Advisory Board to host a geoneutrino detector. In July, the international JUNO collaboration, led by members from the Institute of High Energy Physics, Chinese Academy of Sciences reviewed their recent advances in the construction of the JUNO experiment. Thus, for Chinese geoscience, there is now a new opportunity to become a leader in Neutrino Geoscience.

By 2020, China may have two world class detectors measuring the planet's geoneutrino flux and defining the complement of radioactive power remaining in the mantle. These detectors of course will also address major questions in physics. The JUNO detector is looking into the nature of the neutrino, determining its mass hierarchy (which flavor state of the three known types (electron, muon, or tau) is heavier or lighter [2]) and determining their absolute masses. The proposed Jinping detector will interrogate the Earth's geoneutrino flux as well as the CNO burning cycle of the Sun.

Determining the planet's Th and U contents and, with sufficient statistics (with JUNO being 20 times larger than the existing detectors, it will gather the data to separate the contributions of Th and U), its Th/U ratio can bring

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resolution to several major issues in Earth sciences, such as (1) what are the building blocks used to make the planet; (2) what is the present-day proportion of radiogenic heat relative to the residual heat of accretion, core formation, and extinct nuclides; (3) what is the present-day fraction of radiogenic heat in the continental crust relative to that in the mantle; and (4) what is the composition of the bulk silicate Earth, upper mantle, and lower mantle? Answers to these questions will in turn define for us the power that is driving plate tectonics, mantle convection, and the geodynamo, as well the structure of mantle convection.

This year marks the 10th anniversary of the first paper on detecting geoneutrinos. Achievements of this decade include (1) first detection of the Earth's flux of geoneutrinos [3], (2) demonstration that we can exclude models that invoke a fully radiogenic Earth [4], a fraction of the Earth's surface heat originates from the primordial energy of accretion and differentiation, (3) the first estimate of the mantle signal from a combined analysis of data from the existing KamLAND (Japan) and Borexino (Italy) detectors [5], and (4) a refinement of the Th and U geoneutrino flux at KamLAND of $(3.4 \pm 0.8) \times 10^6\ \mathrm{cm}^{-2}\ \mu\mathrm{s}^{-1}$ [6] and Borexino $(5.0 \pm 1.8) \times 10^6\ \mathrm{cm}^{-2}\ \mu\mathrm{s}^{-1}$ [7]. Prospects for the next 10 years are bright, and we can expect to see (1) a well-defined, mantle signal that excludes some models of the bulk silicate Earth at the level of ≥ 1 sigma; (2) a direct measurement of the Earth's Th/U ratio; (3) detectors measuring hundreds of geoneutrino events/year; and (4) the possibility of an ocean-based detector conducting neutrinographic surveys of the mantle.

This letter is a call for action to let the community know that there are many tasks for Chinese geoscientists in these multi-disciplinary experiments. Importantly, we need to train the next generation of geoscientists in the emerging field of Neutrino Geoscience, which integrates data from the fields of geology, geophysics, and geochemistry. Our future is in developing scientists who are capable of bridging traditional boundaries between these fields.

A prerequisite step involves building a 3D reference model [8], which assigns physical and chemical states to lithospheric voxels (volume element equivalents to pixels) around these detectors and the globe. Experience tells us that in the continents, the closest 500 km to the detector contributes half of the signal, and it is this region that needs critical evaluation. The geoneutrino detectors are most sensitive to a $1/r^2$ relationship, or source-detector separation distance. By predicting the geoneutrino flux at a detector, before it is measured, we test our reference model, which is our description of the composition and structure of the crust and mantle.

Predicting the geoneutrino signal at JUNO demands, we accumulate basic geological, geochemical, and geophysical data for the region surrounding the detector. We must define the physical (e.g., density and structure) and chemical (e.g., abundances and distribution of Th and U) states of the continent (upper, middle, and lower crust). Doing so brings key fundamental benefits to the geoscience community. The combined geological, geophysical, and geochemical data will be integrated into a three-dimensional reference model of the lithosphere. After building this geological model, geologists and particle physicists will work together to calculate the regional geoneutrino flux. The area of the JUNO experiment is close to the continental margin of south China. Beyond the shores of this area is a significant continental shelf. This regional study therefore represents a golden opportunity to investigate in detail a passive continental margin, a tectonic boundary that we know little of its nature (Fig. 1).

JUNO represents a superb opportunity to measure the geoneutrino flux in southern China. The detector's unprecedented size (20 times bigger than all previous detectors) and sensitivity (factor of 2 improvements over

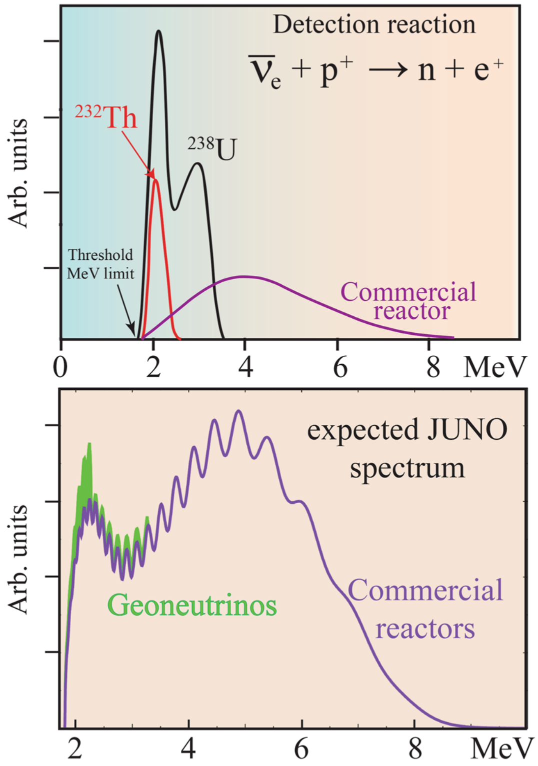

Fig. 1 (Color online) Electron antineutrino spectra from geoneutrinos (^{232}Th and ^{238}U) and reactor neutrinos (commercial reactor). This ideal spectrum assumes an Earth having Th/U = 4.0 and the closest nuclear reactor is ~1000 km away. Upper Panel shows a signal comparable to that expected at a Jinping detector. Lower Panel shows a signal comparable at JUNO, where the reactor to geoneutrino signal ratio is expected to be ~9 [10, 11]. Detection via the inverse beta decay reaction requires ≥ 1.8 MeV, the threshold limit of energy needed to transform the proton into a neutron and positron. Figure modified after McDonough et al. [1]

existing detectors) will allow for the recording of 300–500 geoneutrino events per year [9]. Preliminary studies carried out without any specific input from regional data [10, 11] estimate the geoneutrino flux at JUNO to be $39.7^{+6.5}_{-5.2}$ TNU (terrestrial neutrino unit (TNU), which is geoneutrino events measured per year in a 1-kton detector operating at 100 % efficiency). Moreover, the above studies identified significant regional targets requiring further investigations to predict better the JUNO geoneutrino signal.

In the middle of the Eurasian continent, positioned on the eastern slopes of the Himalayas, and south of the Sichuan Basin, the Jinping detector will provide a fantastic opportunity for fundamental research in geoneutrino studies. A kiloton liquid scintillation detector in this location would represent a breakthrough in geoneutrino research. It would be approximately 1,100 km away from any nuclear reactor, sited in 50+ km thick continental crust in the middle of Eurasia, and could examine models for lower crustal evolution, particularly involving crustal flow and the role that hot, radioactive-rich lower crust reduces the viscosity and enhances the lateral flowing in the regional crust.

The full strength of geoneutrino studies comes from the synergistic activities of geology and physics, neither acting independently of the other and both accepting the challenge of knowing better the Earth and its secrets. These studies represent the ultimate opportunity for geologists and particle physicists to independently measure and test our predictions of the structure and composition of the planet's interior. Thus, by 2020, when these detectors begin counting, we will have our best prediction of the expected signal. It is rare moment in geology where we predict and then receive independent assessment of the strength of our prediction.

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