The R&D progress of the Jinping neutrino experiment

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Abstract. China JinPing underground Laboratory (CJPL) is located about 2400 m below Jinping mountain, providing a unique feature for studies of low-energy neutrinos. A neutrino experiment has been proposed to perform an in-depth research on solar neutrinos, geo-neutrinos and supernova relic neutrinos at Jinping. The physics motivations, the R&D efforts and the present status are reported for a proposed kilo-ton neutrino detector at Jinping. The future prospects are also given.

1. Introduction
China JinPing underground Laboratory (CJPL) is located around 2400 m below Jinping Mountain in the southwest of Sichuan Province, China. Yalong River Hydropower Development Company has drilled four head-race, one drainage and two traffic tunnels through the mountain for a power station around that area. Each tunnel measures about 17 km long. The lab was initially constructed in the middle of the traffic tunnels for dark matter experiments at the end of 2009[1, 2]. The second phase expansion of CJPL started in the end of 2014. The civil construction for the four 150 m long and 12 m wide tunnels was completed in the end of 2016. Two pits were also excavated for future dark matter and neutrino experiments.

CJPL is one of the ideal sites for low-energy neutrino experiments in the world. CJPL has undergone two phases of construction. The first phase (CJPL-I) was done with about 4 km$^3$ rock evacuation, while the second phase (CJPL-II) was enlarged to about 400 km$^3$ with possible further expansion. A number of environmental measurements were done in CJPL-I, recording $(2.0\pm0.4)\times10^{-10}$ cm$^2$·s$^{-1}$ for the cosmic-ray flux, $34\pm7$ Bq·m$^{-3}$ for the average Radon level, 37% average humidity and 21°C average temperature. In addition, CJPL is geographically at least 1000 km away from commercial nuclear power plants either in operation or under construction, leading to having both the lowest cosmic-ray and reactor neutrino background fluxes among the underground labs. Figure 1 shows a comparison of cosmic-ray and reactor electron anti-neutrino fluxes with others in the world.

As shown in Fig. 2, the proposed neutrino experiment consists of a pair of two liquid scintillation Cherenkov detectors, with a fiducial mass of two kilotons and the capability to detect both energy and directional information.

2. Physics motivations at Jinping
We focus on three major physics topics for solar neutrinos, geo-neutrinos and supernova relic neutrinos with energy below a few of tens MeV. Assuming a collection of 500 photo-electrons per
MeV and a low background level similar to the Borexino experiment, a number of sensitivities were investigated.

Solar neutrinos are the only direct probe of the solar interior. Because of the depth of CJPL, the level of cosmogenic $^{11}$C is expected to be reduced by two orders of magnitude in comparison to the Borexino experiment. This will be very helpful in studying the solar neutrino oscillation between 1 MeV and 3 MeV, in which the oscillation is at the transition phase from the vacuum to the matter effect and has not been addressed by the present solar neutrino experiments. Our simulation study shows that Jinping can provide a critical test for the Mikheyev-Smirnov-Wolfenstein (MSW) theory in the high-density environment and also has the potential to discover solar neutrinos from the carbon-nitrogen-oxygen (CNO) cycle, with more than 5σ of statistical significance [3].

Geo-neutrinos are from the radioactive decays from the $^{238}$U, $^{232}$Th and $^{40}$K in the Earth. Since CJPL is located in the mountain area of the Himalayas with a much thicker crustal layer, it is expected that the geo-neutrino flux is about 50% more than that in the other underground labs [4]. The dominant crustal geo-neutrinos will provide a relatively clean environment to test the Earth’s models, and can also give a stringent constraint on the geophysical prediction for the Lithospheric flux and unveil the mantle contribution to the total geo-heat budget. Since the geo-neutrino signals are dominated by the inverse beta decay chain with an energy threshold 1.8 MeV, only those from the decay chains of $^{238}$U and $^{232}$Th can be observed. The electron anti-neutrinos from nuclear power plants are the more important background. Fortunately, this background in the signal region from 1.8 to 3.3 MeV was estimated to be (60.4 ± 0.9) events/3kt/1,500 days, which is significantly less than 527.3 geo-neutrino signal events (414.5 for $^{238}$U and 113.6 for $^{232}$Th). With an exposure of 3 kt×1,500 days, Jinping can measure the geo-neutrino flux with a precision of 4.6% without assuming a fixed Th/U ratio, and this ratio can also be independently determined with a precision of 26.3%. In addition, the suggested 3-30 TW Earth core fission reactor can be either confirmed or excluded within 300 live days [5]. It is found that with the directional information gained in the liquid scintillator Cherenkov detector the Mantle and $^{40}$K components of geo-neutrinos can also been detected through the elastic scattering between the electron anti-neutrino and the electron [6]. Directional information will play a crucial role in identifying these geoneutrinos from the solar neutrino background.

The proposed Jinping neutrino experiment can also be used to search for supernova relic neutrinos (SRN’s) from past Galactic core-collapse supernovae. These SRN’s have never been observed because of the potential spallation background in most of the low-energy neutrino
experiments. The cosmogenic $^9\text{Li}/^8\text{He}$ background can fake an inverse beta decay chain via a $\beta + n$ cascade decay and becomes an irreducible background. Even though the target mass is only a few kilotons at Jinping, an exposure of 20 kiloton-years at Jinping could still have a $3.5\sigma$ significance-level of discovery at Jinping [7]. This is due to the fact that the liquid scintillator Cherenkov detector allows us to use both energy and directional information to significantly suppress the atmospheric neutrino background.

3. Detector R&D

A new type of liquid scintillator, with high light-yield and Cherenkov and scintillation separation capability, is being developed for the proposed Jinping neutrino experiment. The technique is based on Linear Alkyl Benzene (LAB) with a controlled resolution of wavelength shifter and fluorescer. The pulse shape of the scintillation light is stretched to several tens of nanoseconds, allowing the prompt Cherenkov light component to emerge. The scintillator is also referred to as the slow liquid scintillator. By fitting the pulse shape from the photon-multiplier tube (PMT) both sources of light can be separated and thus, provide independent measurement of energy and direction. From our bench test, the liquid scintillator cocktail with 0.07 g/L PPO and 13 mg/L bis-MSB can give a light yield up to about $3.4 \times 10^4$ photons/MeV. This technique was tested in a 20L container [8, 9]. Figure 3 illustrates the waveform of a cosmic-ray muon going through the 20L container containing the pure LAB. In this set-up, one PMT was placed on the top of the container to detect the scintillation light, while the other one was attached to the bottom to detect both the scintillation light and the Cherenkov light.

![Fig. 3. The average waveform from the PMT. All the cosmic-ray muons went from the top to the bottom. Since the Cherenkov light is forward, it can only be detected by the bottom PMT. Both PMTs can detect the uniform scintillation light.](image)

![Fig. 4. Design sketch of the proposed light concentrator for the Jinping neutrino experiment.](image)

Collecting sufficient light is very important for the studies of low-energy neutrinos. We investigated light concentrators at Jinping to ensure a high coverage but without sacrificing much the timing resolution. These concentrators are known as Winston cones and have been applied in many low-energy neutrino experiments. Using a hexagonal opening and a 3D modification of the String method that was previously used to design the concentrators, we optimized the design and obtained a 90-degree wide field view and more than 98% efficiency for optical photon...
collection at a cost of 2 ns time spread. It was estimated to save about 20% of PMTs for the same coverage [10]. Figure 4 demonstrates the design sketch of the light concentrator.

The assay and selection of low radioactive stainless-steel (SST) was done. Taking the advantage of low background environment at CJPL, we examined the radioactivity of stainless steel from raw materials to stage samples and commercial products, by using a high-purity germanium detector (HPGe). The U and Th concentration in the custom-made stainless steel samples is found to be less than $10^{-8}$ g/g for selected SST samples and is comparable with other low-background neutrino experiments [11].

To test the technique of liquid scintillator Cherenkov in a relatively large scale detector, we designed and built a one-ton prototype detector at CJPL [12]. As shown in Fig. 5, a 1.29 m diameter acrylic ball containing one-ton of slow liquid scintillator is installed in a steel cylinder. There are 30 8-inch Hamamatsu R5912 PMTs attached outside the acrylic ball. Pure water is filled between the acrylic ball and the steel tank. In order to shield external gamma rays, there is a layer of 5-cm thick lead bricks outside the tank. This prototype detector started operation in a pure water mode in May, 2017. The PMT dark noise was observed to decrease following an exponential law. Cherenkov rings produced by beta-rays in pure water were also seen. After the three-month run in water mode, the prototype detector was switched to the slow liquid scintillator mode in August. With this prototype, we can also study the features of the PMTs, including the noise, the gain and the performance. Once the PMT calibration is completed, we will start to study the waveforms of internal gamma-rays and beta-rays from all the PMTs.

![Figure 5. The sectional view of the one-ton prototype detector at Jinping. Each component is also indicated in the plot.](image)

A Geant4 based simulation & analysis package has been prepared for the Jinping neutrino experiment. This package can provide a comprehensive optical simulation with flexible to different geometrical set-up. The waveform simulation is also included. We will study the performance of the liquid scintillator Cherenkov detector from both the real data and the simulation before we can finalize the design of the kilo-ton neutrino detector at Jinping.
4. Future prospects

CJPL as the deepest underground facility with low radioactive background for frontier physics experiments, has been listed into the 13th Five-Year Plan for major science and technology infrastructure development of China. The Jinping neutrino experiment can make a significant contribution to solar neutrino physics, geo-neutrino science and supernova relic neutrino search. The one-ton prototype detector is now taking data, which can provide us much more information on how the liquid scintillator Cherenkov detector is working. Many R&D studies are still ongoing. In early 2017, the international advisory committee of CJPL gave a recommendation to build a strong collaboration and formulate an optimal strategy for advancing to a large, deep and unique observatory for low-energy neutrinos. We expect to have a 10-ton scale prototype to test the achievable background level in the coming two years and hope to start the construction of kiloton neutrino detector around 2020.

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References

[1] CDEX Collaboration, Front.Phys.(Beijing) 8 (2013) 412-437.
[2] PandaX Collaboration, Sci. China Phys.Mech.Astron. 57 (2014) 1476-1494.
[3] J. F. Beacom et al., Chinese Physics C Vol. 41, No. 2 (2017)023002.
[4] O. Šrámek et al., Sci. Rep. 6, 33034.
[5] L. Wan et al., Phys. Rev. D95 (2017) no.5, 053001.
[6] Z. Wang & S. Chen arXiv:1709.03743.
[7] H. Wei et al., Phys. Lett. B 769(2017) 255-261.
[8] M. Li et al., Nucl. Instrum. Meth. A830 (2016) 303-308.
[9] Z. Guo et al., arXiv:1708.07781.
[10] Y. Zhi et al., Nucl. Instrum. Meth. A885 (2018) 114-118.
[11] G. Hussain et al., Nucl. Instrum. Meth. A881 (2018) 65-71.
[12] Z. Wang et al., Nucl. Instrum. Meth. A855 (2017) 81-87.