The common experimental platform construction of Jinping deep underground laboratory for nuclear astrophysics: sub-program of JUNA

Abstract

The accurate measurement of key reactions based on underground laboratory has been an international frontier of nuclear astrophysics. The project aims to build the first deep underground experimental platform for nuclear astrophysics at Jinping tunnel where the rock overburden provides the thickest shielding (6720 meters of water equivalent). The main contents include: the accurate determination of the background level of the laboratory; the optimization of the high current and high stability accelerator system; the design and installation of the experimental shielding system; the research and development of the superpower solid target. As the basis, the project will support the study of the four physics projects and lay a good foundation for the subsequent experiments. The Jinping underground laboratory is the deepest laboratory in the world, leading to a two orders of magnitude reduction in the cosmic-ray flux compared to LUNA, and the beam intensity of our platform is about 10 times more than LUNA 400 kV accelerator. Therefore, the project will make it possible for the pioneering study of key nuclear astrophysics reactions, which remain beyond the current capability at LUNA, and the fruitful output will promote the nuclear astrophysics study in China to a world-leading level.

1. Physics background

The astrophysical reaction rate of charged-particle reaction is dominated by the cross section within the Gamow window. In the astrophysical environment at low temperature, the Gamow window is far below the Coulomb barrier, which leads to extremely low cross sections (10^{-18}~10^{-13} barn). Therefore, the direct measurement of the cross sections at astrophysical interested energy region is very difficult due to the extremely low yield, which is significantly interfered by the natural background [1].

The deep underground laboratory can provide a measurement environment with ultra-low background by significantly shielding the cosmic rays, which allows us to perform the experiment with a very low counting rate, e.g., the measurement of cross sections within Gamow windows [2]. Figure 1 shows the comparison between the γ-ray background on the ground and that in the deep underground laboratory. At present, the underground nuclear astrophysical experiments have only been performed by LUNA (Laboratory for Underground Nuclear Astrophysics) project at INFN (Istituto Nazionale di Fisica Nucleare) Laboratori Nazionali del Gran Sasso. This laboratory is shielded by 1400 meter thick rock overburden (about 3800 meters of water equivalent), the cosmic μ meson flux, γ-ray background, and neutron background is 10^{-6} order, 1/2500, and 1/1000 of magnitude lower than those on the ground, respectively. In the past 20 years, the LUNA collaboration has performed several direct measurements of the cross sections near the Gamow window of the key reactions in the Hydrogen burning and the Big Bang nucleosynthesis [3], which produce important impacts on the researches of solar neutrino physics, nucleosynthesis, and cosmology.

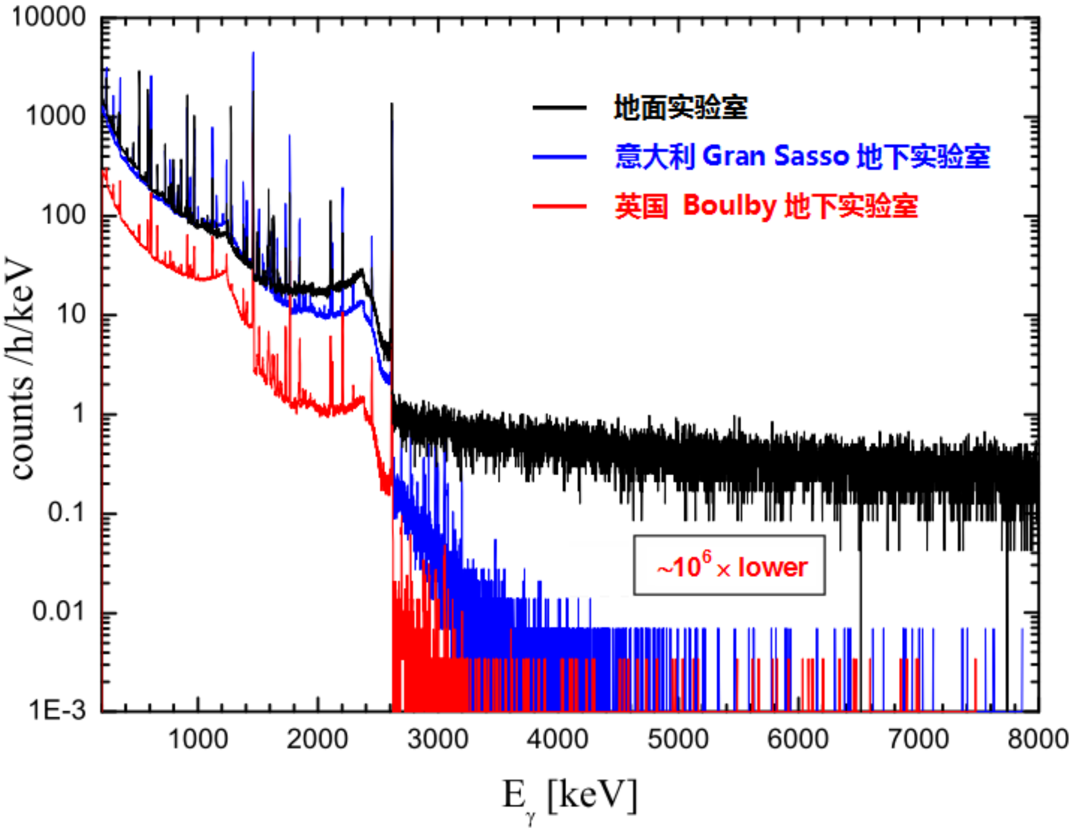

Fig. 1. The comparison between the γ-ray background on the ground and that in the deep underground laboratory.

In recent years, more and more deep-underground projects have been carried out in China, which provides conditions and opportunities for the development of deep underground laboratory. China Jinping Underground Laboratory (CJPL), which is based on the traffic tunnel of the Jinping hydropower project, is the deepest underground laboratory in the world [4-6]. At present, two experimental projects, the Particle and Astrophysical Xenon (PandaX) and the China Dark Matter Experiment (CDEX)，are running for searching the dark matter in CJPL. In 2015 the second phase of CJPL project will newly build eight experimental halls with a length, width, and height of 50, 12, and 12 meters, respectively. According to the agreement between Tsinghua University and China Institute of Atomic Energy, one new experimental hall will be used for the nuclear astrophysics experiment research.

With the increasing attention of nuclear astrophysics experiment in underground laboratory, there are several underground nuclear astrophysics project have been proposed: The CASPAR project proposed by DIANA collaboration in America [7], the ELENA project proposed by Boulby underground laboratory in England [8], the CUNA project proposed by LCS underground laboratory in Spain [9]. Figure 2 shows the comparison of the depth and background between CJPL, LUNA, and other underground nuclear astrophysics laboratories in plan. One can see that CJPL has not only the largest depth, but also the lowest background.

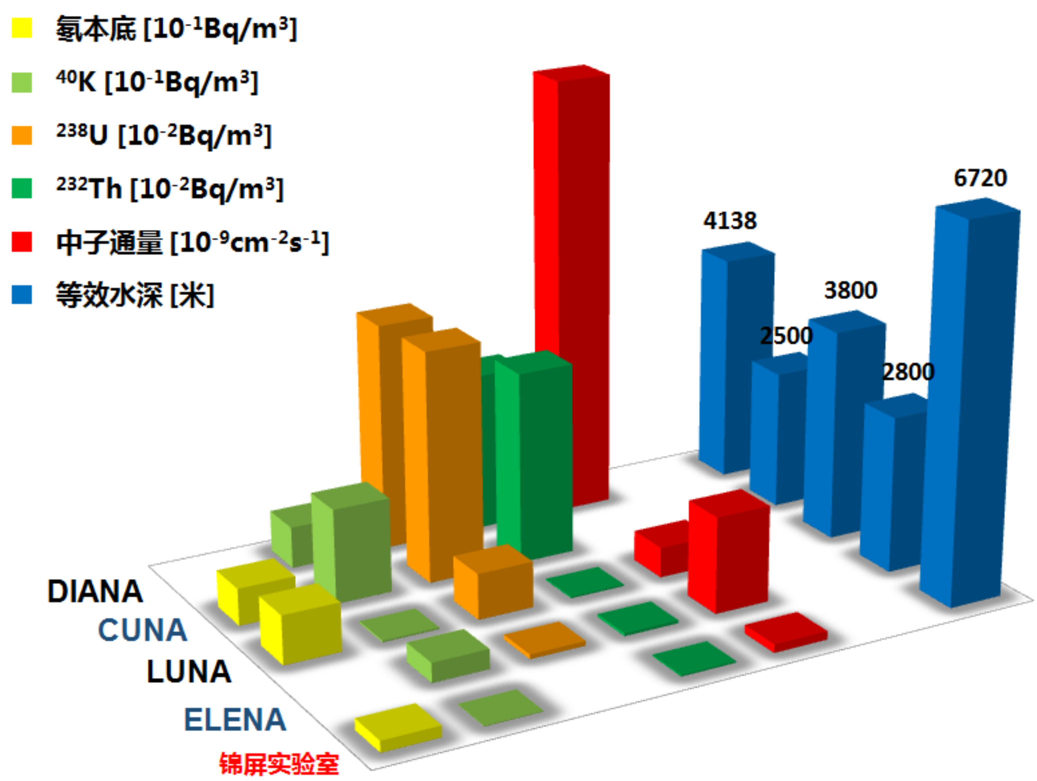

Fig. 2. Comparison of the depth and background between CJPL and other underground nuclear astrophysics laboratories in the world.

Taking the advantage of ultralow background in CJPL, the current project "The common experimental platform construction of Jinping deep underground laboratory for nuclear astrophysics" relying on CIAE and Tsinghua University will build the first experimental platform for underground nuclear astrophysics in China. This project will support the studying of four physics programs in the major research project, building the detection and shielding system of the γ-ray, neutron, and charge particles, and lay out a solid foundation for the following researches for above four key nuclear reactions in astrophysics.

2. Scientific program

2.1 The accurate determination of the background level of the laboratory and

construction of a ultralow background test platform

Although the background of CJPL has already been measured in the CDEX and PandaX projects, we still need to measure the γ-ray background at high energy region that astrophysics nuclear reaction study is interested since the focus of the dark matter research is the neutron and low-energy γ-ray background.

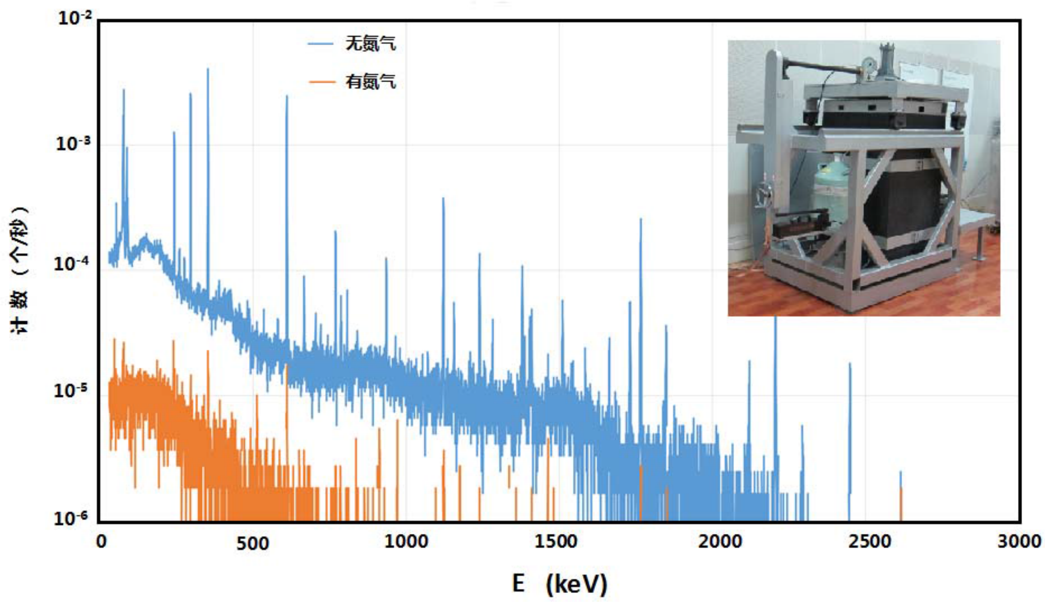

Fig. 3 Low background γ-ray spectrometer (GeTHU) built by Tsinghua University and its measurement result.

In order to select the low background materials for the laboratory construction, we need to build an ultralow background test platform. Figure 3 shows the low background γ-ray spectrometer (GeTHU) built by Tsinghua University and its measurement result. We plan to develop an ultralow background test platform based on GeTHU and perform the background test of the materials.

2.2 The optimization of the high current and high stability accelerator system

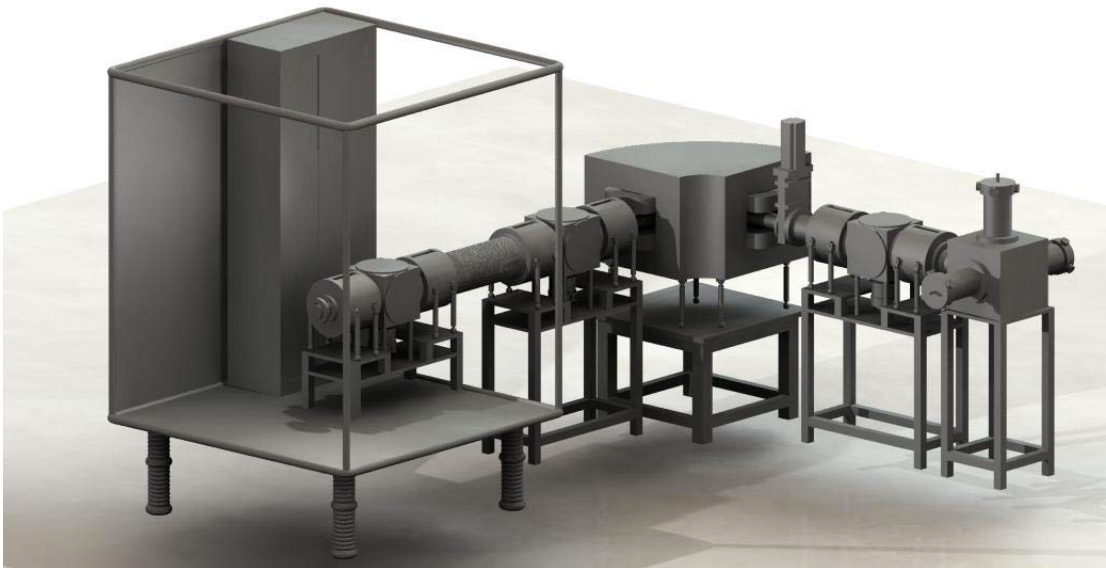

Fig. 4. Low energy and high current accelerator system of JUNA.

Figure 4 is the preliminary design of the low energy and high current accelerator system of JUNA. For ensuring better progress in other four physics programs of the major research project, we plan to optimize the accelerator system based on the preliminary design. Specific measurement include:

I. Developing a high stability power supply system

For the nuclear reaction measurement at Gamow window, the long-term stability is the key to achieve the high measurement precision. Hence we must use the high-voltage power supply with high stability. We plan to cooperate with Glassman High Voltage, Inc and develop a 400 kV, 6 kW high stability power supply (long-term output voltage stability < 0.05%, ripple voltage<0.01%).

II. Optimizing the design of the accelerating tube

As the low energy and high intensity beam, the space-charge effect must be restricted during transmission in order to increase the transport efficiency. The high transport efficiency could not only ensure enough beam intensity on target, but also reduce the background brought by the beam itself. We plan to adopt segmental applying voltage for the accelerating tube and design an acceleration and deceleration alternating distribution structure for the accelerating tube electrode to reduce the space-charge effect.

III. Enhancing the ability of the analyzing magnet

This accelerator system uses ECR ion source, which can provide high intensity H^+, He^+ and He^{2+} beams. There is about 1% H_2^+ impurity in He^{2+} beam, which will make disturbances to the measurements of (α, γ), (α, n) reactions. Hence we need to enhance the separating capability of the analyzing magnet and reduce the content of the H_2^+ in He^{2+} beam by one or two orders of magnitude.

2.3 The design and installation of the experimental shielding system

The effect to background ratio of the nuclear reaction measurement will be significantly enhanced with the ultralow background of CJPL and high current beam. But at the same time the high current beam will bring new background, which must be shielded. We plan to construct two shielding system around the target chamber and the detectors, aiming at γ-ray and neutron, respectively.

In order to avoid the influence to other laboratories in CJPL, we plan to cover the accelerating tube with Lead shielding layer and build a concrete shielding wall in our laboratory to insulate the background coming from accelerator.

2.4 The research and development of the superpower solid target

In order to keep the stability of the solid target under the bombardment of high current beam, we plan to develop a superpower solid target system. The temperature of target will be effectively controlled by good design of heat conduction and water cooling device. The design power of the superpower solid target system is 20 kW/cm^2, which can satisfy the requirement of the four experiments in the main project.

3. Summary

In summary, the main focus of this sub-program is,

1) Measuring the background in Jinping Underground Laboratory, which includes the γ-ray and neutron background; building the low-background material-testing platform.
2) Improving the accelerator manufacture, the stability of system, the efficiency of beam transmission; Suppressing the background coming from the intense beam.
3) Establishing the γ-ray and neutron shielding system and shielding the nuclear astrophysics experiment platform to ensure the low-background environment.
4) Developing the high-power solid target system to satisfy the requirement of the long-time experiment.

This sub-program is the foundation of the entire major project. With the advantage of extremely low background in Jinping Underground Laboratory, we will build the best nuclear astrophysics underground laboratory around the world, and establish the systematic experimental methods of the direct measurement in the underground laboratory.

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