Snowmass2021 - Letter of Interest

Searching for $0\nu\beta\beta$ decays in JUNO

NF Topical Groups: (check all that apply ☐/■)
☐ (NF1) Neutrino oscillations
☐ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications
☐ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
☐ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: It is extremely important for future neutrinoless double-beta ($0\nu\beta\beta$) decay experiments to reach a sensitivity to effective neutrino mass $|m_{\beta\beta}| \approx 1\ \mathrm{meV}$. At this level, the determination of absolute neutrino masses and the constraints on one of two Majorana CP phases are possible. The currently planned ton-scale double-beta decay experiments aim for $|m_{\beta\beta}| \approx 10\ \mathrm{meV}$, corresponding roughly to the lower boundary of $|m_{\beta\beta}|$ in the inverted mass ordering case. However, such sensitivity would not allow to explore the normal mass ordering region, which is slightly favored by recent atmospheric and accelerator neutrino data. The JUNO experiment has great potential to be upgraded to search for $0\nu\beta\beta$ and to reach a sensitivity of $|m_{\beta\beta}| \approx 1\ \mathrm{meV}$ after its primary mission on the determination of neutrino mass ordering and the precision measurement of three oscillation parameters is accomplished. A dedicated R&D program focused on the purification and doping of liquid scintillator with a suitable $0\nu\beta\beta$-decaying isotope, as well as on the development of advanced techniques for background rejection, will be carried out in the next few years. If successful, JUNO could be ready to begin searching for $0\nu\beta\beta$ decays at the turn of the next decade.

Key words: neutrinoless double-beta decays, absolute neutrino masses, JUNO

Physics Motivation

In a class of seesaw models for neutrino mass generation [1], massive neutrinos are Majorana particles that can provide a natural and elegant explanation for the observed matter-antimatter asymmetry in our Universe. If this is indeed the case, it will be a great challenge to determine the two associated Majorana-type CP-violating phases, which are measurable only in lepton-number-violating processes. The experimental search for neutrino-less double-beta ($0\nu\beta\beta$) decays is the most promising way to determine the Majorana nature of massive neutrinos and to prove the existence of lepton number violation in nature.

The next-generation $0\nu\beta\beta$ decay experiments aim for an effective Majorana neutrino mass $|m_{\beta\beta}| \approx 10~\mathrm{meV}$, which corresponds roughly to the lower boundary of $|m_{\beta\beta}|$ in the inverted mass ordering case. Such sensitivity is not sufficient to observe a potential signal in the normal mass ordering case, which is slightly favored by the latest global-fit analysis of neutrino oscillation data [2]. However, with a sensitivity of $|m_{\beta\beta}| \approx 1~\mathrm{meV}$, it is likely to observe the signals. A null result of the $0\nu\beta\beta$ decays does not mean that massive neutrinos must be of Dirac nature, and there is always a small parameter space for $|m_{\beta\beta}| \to 0$ even though no other exotic new physics is introduced. If the sensitivity of 1 meV is ultimately realized, the determination of absolute neutrino masses and the constraints on one of two Majorana CP phases are possible [3], the latter of which are not accessible in other types of neutrino experiments, such as beta decays [4] and cosmological observations [5]. The AstroParticle Physics European Consortium (APPEC) Committee has recently recommended that a program of R&D should be devised on the path towards the meV scale for the effective Majorana neutrino mass [6].

The Potential of JUNO

The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose experiment focused on precision measurements of neutrino oscillations and the exploration of neutrino astrophysics [7]. JUNO features a 20 kton ultra-low-background liquid scintillator (LS) detector with $3\%/\sqrt{E~(\mathrm{MeV})}$ energy resolution, which is now under construction. A Letter of Interest (LOI) focused on the JUNO experiment and its physics program was submitted separately [10].

After JUNO completes its primary mission of determining the neutrino mass ordering and precisely measuring three oscillation parameters, the detector can be upgraded to pursue another ambitious physics goal, i.e., the determination of absolute neutrino masses. JUNO has great potential of searching for $0\nu\beta\beta$ decays by dissolving the $0\nu\beta\beta$-decaying ^{130}Te ($Q_{\beta\beta} = 2527.5~\mathrm{keV}$) or ^{136}Xe ($Q_{\beta\beta} = 2457.8~\mathrm{keV}$) isotope into the LS. The preliminary studies in Ref. [8] have demonstrated that if the JUNO detector is upgraded with ~50 tons of ^{136}Xe-loading in future, a sensitivity of $|m_{\beta\beta}| \approx 5~\mathrm{meV}$ is achievable when the most optimistic value of the nuclear matrix element is considered. In order to improve the sensitivity to $|m_{\beta\beta}| \approx 1~\mathrm{meV}$, one has to remarkably increase the target mass and reduce the backgrounds. The required large scale ^{136}Xe enrichment, e.g., tens of tons, remains by itself a major challenge, which may be addressed by developing a cost effective technique and a dedicated research facility in future. It appears more promising at this point to achieve $|m_{\beta\beta}| \approx 1~\mathrm{meV}$ by developing the ^{130}Te-loaded LS (Te-LS) to reach a sufficiently large target mass [11].

Management of both internal and external backgrounds will be critical. JUNO already aims to achieve an internal LS radiopurity of $10^{-17}~\mathrm{g\,g^{-1}}$ ^{238}U/^{232}Th for low-energy solar neutrino measurements. Previous studies suggest that such radiopurity is necessary for searching for $0\nu\beta\beta$ decays. JUNO is at a relatively shallow depth of ~700 m rock overburden, but previous studies suggest that backgrounds from muon spallation at such depths could be sufficiently suppressed using time and volume cuts around the reconstructed muon track. Furthermore, deep learning techniques will be crucial to topologically discriminate the $0\nu\beta\beta$

from the irreducible backgrounds arising from the two-neutrino-emitting double-beta decays ($2\nu\beta\beta$) and the recoiled electrons due to their elastic scattering with solar ^{8}B neutrinos. Deep learning will also be very helpful in suppressing cosmogenic backgrounds.

Tentative Timeline

The R&D is foreseen to continue until 2028. During this period, the techniques for loading Xe or Te into LS, as well as an online LS purification system satisfying all the requirements, will be developed. Pilot plants for Te-LS production and purification will be built and the loaded LS characterized in the OSIRIS detector [9], which is a 20 ton detector serving as a radioactivity monitor for JUNO's LS. Powerful analysis techniques needed for background rejection, such as approaches based on deep learning, will also be developed. These will be optimized and benchmarked using the data from the first phase of the JUNO experiment.

The construction upgrade for the $0\nu\beta\beta$ search at JUNO is expected to start in 2029 and to last for about two years. Then, with another ten years of running, a sensitivity of $|m_{\beta\beta}| \approx 1\ \mathrm{meV}$ will be reached if a fiducial mass of ~250 tons of $0\nu\beta\beta$-decaying isotopes and a background level of ~0.02 $\mathrm{ROI}^{-1}\ \mathrm{ton}^{-1}\ \mathrm{yr}^{-1}$ can be obtained.[1]

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[1] Here ton is a unit of the mass of the $0\nu\beta\beta$-decaying isotope

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