A Large Water-Based Liquid Scintillation Detector in Search for Proton Decay $p \rightarrow K^+\bar{\nu}$ and Other Physics

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We describe the approach of a large water-based liquid scintillation (WbLS) detector in search for proton decay as part of the Intensity Frontier effort. The potential transitions from such detector to neutrinoless double beta decay (DBD) and other physics frontiers are also discussed. The search for $p \rightarrow K^+\bar{\nu}$ mode in large water Cherenkov detectors is hindered by the kinematics of the initial $K^+$ (105 MeV, below the Cherenkov threshold). The current best limit of $\tau(p \rightarrow K^+\bar{\nu}) > 2.8 \times 10^{33}$y at 90% C.L. comes from Super Kamiokande, which uses a 6.3-MeV $\gamma$-ray transition to tag proton decays inside oxygen nuclei. An enhancement to the water Cherenkov detector by the dissolution of scintillation liquid in the ultrapure water is proposed. The addition of scintillator to the water Cherenkov detector will have two consequences: ionizing particles below the Cherenkov threshold in water ($\beta < 0.75$) become detectable by their scintillation light, and the atmospheric $\nu_\mu$-induced $\mu^+$ background can be further suppressed. A full Geant4 Monte Carlo simulation of the WbLS (90 optical photons per MeV and $\lambda_{1/\phi} \sim 60$) in a SK-like cylindrical detector shows that after 10 years of running time, only 0.1 background events are expected and a limit of the proton lifetime at $\tau > 2 \times 10^{34}$y at 90% C.L., an order of magnitude improvement over the current limit, can be achieved (see Figure). In addition, the ability to detect the 2.2-MeV capture gamma will reduce background for essentially all modes, as real proton decay events are unlikely to be accompanied by a free neutron, whereas atmospheric neutrino events at proton decay energies will often have a neutron in the final state. The detection of anti-electron neutrinos $\overline{\nu}_e$ can also be made by such a detector through the inverse beta decay (IBD) process ($\overline{\nu}_e + p \rightarrow n + e^+$). Furthermore the WbLS is capable of loading any metallic ions of interest (e.g. $^6$Li for short-baseline reactor anomalies or Gd for neutron tagging enhancement). The same water-based detector could also serve as the near detector for Hyper-K or be used for detection of diffuse neutrino flux from distant past supernovae. Another extended application of the WbLS is neutrinoless double-beta decay for the determination of neutrino mass and Majorana or Dirac nature. Some DBD candidates that were not previously favorable for small scintillator-based detectors, due to their hydrophilic nature or low nature abundance, are now accessible by the WbLS technology. An increase of double beta decay available mass to the “tens of tons” scale might be possible.

The water-based liquid scintillator is the new cost-effective detection medium for future massive detectors with the unique capability of exploring physics below the Cherenkov threshold. The principal of a mass-producible WbLS has been demonstrated. A deployment of such a scintillating water detector at deep underground laboratory with careful controls of low-energy radioactive background could reach the sensitivity of the SUSY GUT prediction of $10^{34.1}$y with other implications in neutrino and rare-event physics; an economic detector with extensive physics potential for the next-generation frontier experiments.
References