Measuring the Neutrino Mass Hierarchy with Atmospheric Neutrinos

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The neutrino mass hierarchy is one of the key remaining unknowns in the neutrino sector, with important implications in a number of nuclear physics problems, including neutrinoless double beta decay ($0\nu\beta\beta$) and the physics of supernova explosions. $0\nu\beta\beta$ in particular is a key focus of neutrino research in nuclear physics [1].

In $0\nu\beta\beta$, the relationship between the effective mass for neutrinoless double beta decay and the mass of the lightest neutrino depends on whether the mass hierarchy is normal or inverted. If the mass hierarchy is inverted, then there is a minimum effective mass which could be reached by envisioned next-generation neutrinoless double beta decay experiments. If there were an independent measurement of the mass hierarchy, an experiment that reached this limit could conclusively state that neutrinos are not Majorana particles. If the mass hierarchy is normal or unknown, then no such statement is possible. Experiments could observe $0\nu\beta\beta$, but, in the absence of an observation, the nature of neutrinos would remain uncertain.

Directly measuring the neutrino mass hierarchy requires high-resolution measurements of neutrino oscillations. There are a number of proposed methods to do this [2]. The least costly and possibly fastest approach is to use atmospheric neutrinos. Three groups are proposing this: PINGU (Precision IceCube Next Generation Upgrade) in the Antarctic ice cap, ORCA (Oscillation Research with Cosmics in the Abyss) in the Mediterranean Sea [3], and the India-based Neutrino Observatory [4]. Here, we focus on PINGU, which has a large U. S. participation.

PINGU will permit a determination of the mass hierarchy, independent of the CP violation parameter, at relatively modest expense, using a well-understood technique with minimal risk, on a short time scale. It will leverage the knowledge gained in designing, deploying and operating IceCube and its in-fill array DeepCore. IceCube and DeepCore have been continuously taking high-quality physics data since early 2011. By deploying PINGU within and around existing IceCube and DeepCore digital optical modules (DOMs), a multi-megaton fiducial volume of ice would be instrumented with sufficient photocathode density to yield a neutrino energy threshold of a few GeV. The scale of PINGU would permit measurement of the oscillations of atmospheric neutrinos over a range of energies and a variety of baselines (up to the diameter of the Earth) with sufficient precision that hierarchy-dependent distortions of the oscillations due to the presence of matter could be observed. PINGU will also provide a precise measurement of θ_{23}.

PINGU construction and technology would be similar to that used in IceCube, with large photomultiplier tubes and readout electronics encased in pressure vessels embedded in the Antarctic ice cap below the US Amundsen-Scott South Pole Station. The 2850 m thick, very transparent South Pole ice cap would serve simultaneously as neutrino target, Cherenkov medium, and detector support structure.

A likely construction scenario places PINGU under the umbrella of an expanded IceCube-based facility at the South Pole. PINGU would be constructed first, followed by an extension focused on high energy astrophysical neutrinos, obtaining economies of scale through the use of common hardware and installation techniques. The PINGU share of the facility cost is roughly \$55M (US cost, including contingency) plus \$25M (foreign contribution) for a total of

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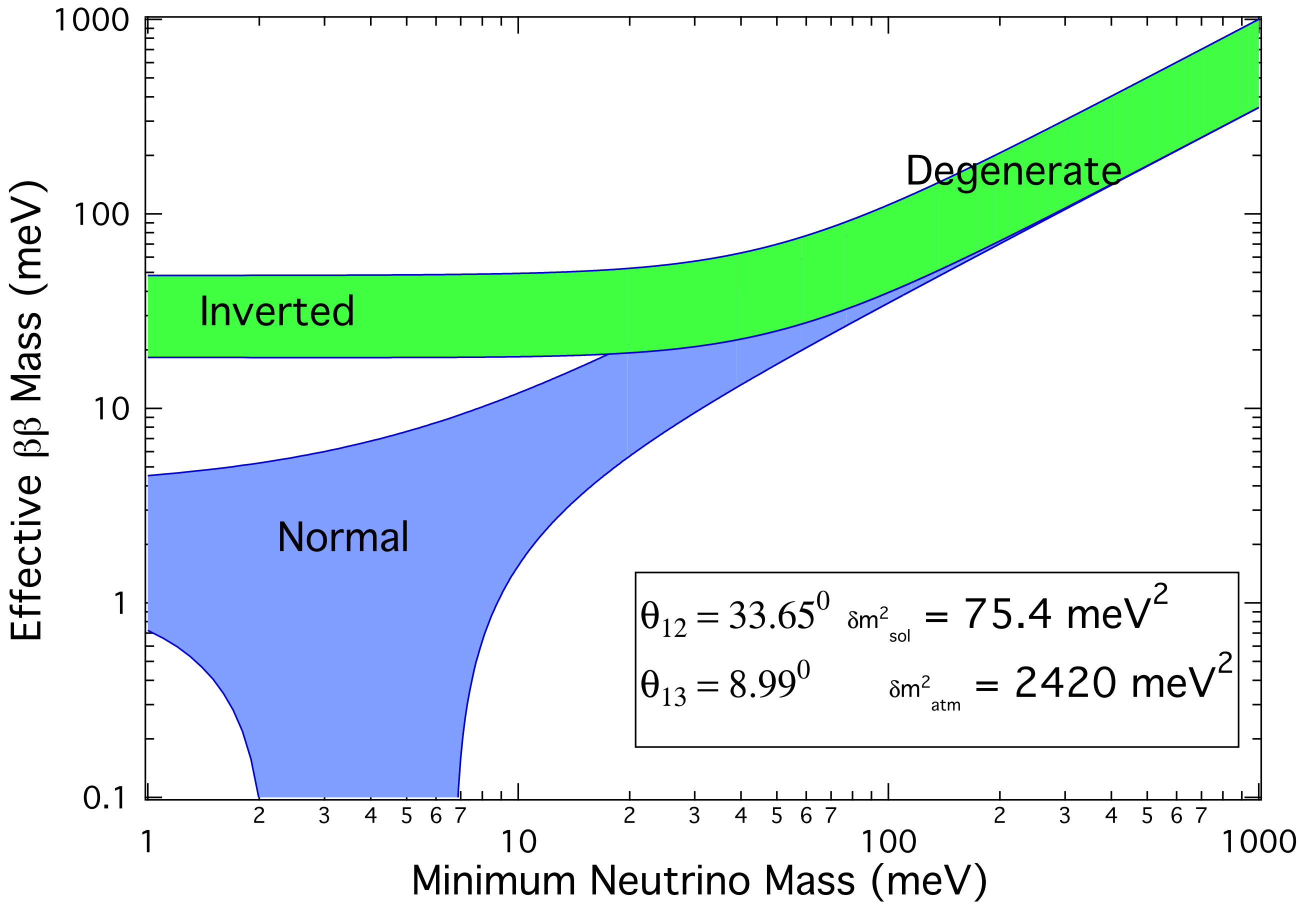

FIG. 1: The effective neutrino Majorana mass $m_{\beta\beta}$ as a function of the lightest neutrino mass, $m_{\rm light}$. The blue (green) band corresponds to the normal (inverted) ordering, respectively, in which case $m_{\rm light}$ is equal to m_1 (m_3). The widths of the bands come from uncertainties in the other neutrino properties. From Ref. [5].

$80M. Detector construction can be completed five years after funding starts, or as early as 2020. The determination of the mass hierarchy at the 3σ level would be possible with about 3 years of data.

A determination of the neutrino mass hierarchy would contribute to advances in a number of other areas in the nuclear physics purview. Knowing the neutrino mass hierarchy is also important for understanding how supernovae explode; neutrinos interact collectively with the matter in supernovae, and the character of these interactions depends on the hierarchy. These differences are important in modelling supernovae [6] and understanding heavy-element production in the universe, and they also have observational consequences [7]. An independent determination of the neutrino mass hierarchy would allow future observations of neutrinos from supernovae to be used to much better pin down other aspects of the supernova explosion process.

PINGU will also become one of a handful of active supernova neutrino detectors. Its multi-megaton fiducial volume gives it the ability to observe galactic supernova with unprecedented (millisecond) time resolution [8], and it will have a phototube density high enough to determine both the integrated neutrino luminosity and the neutrino energy spectrum on short time scales [9].

In conclusion, PINGU offers an extremely cost effective way to provide answers to the key (and still relevant) question posed in the 2007 Nuclear Science Long Range Plan [10], “What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the universe?” PINGU will use atmospheric neutrinos to determine the neutrino mass hierarchy, with a direct impact on the interpretation of $0\nu\beta\beta$ measurements, the modelling and understanding of supernova explosions, and the detector will serve as a premier supernova neutrino detector in its own right.

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