The Majorana project

Steven R Elliott for the Majorana collaboration
Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA 87545
E-mail: elliotts@lanl.gov

Abstract. The objective of the Majorana experiment is to study neutrinoless double beta decay $\beta\beta(0\nu)$ with an effective Majorana-neutrino mass sensitivity near 100 meV in order to characterize the Majorana nature of the neutrino, the Majorana mass spectrum, and the absolute mass scale. An experimental study of the neutrino mass scale implied by neutrino oscillation results is now technically within our grasp. This exciting physics goal is best pursued using the well-established technique of searching for $\beta\beta(0\nu)$ of $^{76}\text{Ge}$, augmented with recent advances in signal processing and detector design. The Majorana experiment will consist of a large mass of $^{76}\text{Ge}$ in the form of high-resolution intrinsic germanium detectors located deep underground within a low-background shielding environment. Observation of a sharp peak at the $\beta\beta$ endpoint will quantify the $\beta\beta(0\nu)$ half-life and thus the effective Majorana mass of the electron neutrino.

1. Introduction
The physics motivation for double-beta decay experiments is very compelling. (See for example recent reviews [1] and [2].) Zero-neutrino double-beta decay ($\beta\beta(0\nu)$) can only occur if neutrinos are massive Majorana particles. Hence experiments searching for this hypothetical process address two of the fundamental properties of neutrinos: their mass and whether lepton number is conserved. It is now possible for next-generation $\beta\beta(0\nu)$ experiments to access the neutrino mass range of interest suggested by recent studies of neutrino oscillations. A well-designed germanium detector array can find the effective mass, if the massive neutrinos are Majorana particles and the neutrino mass spectrum is quasi-degenerate or inverted hierarchy. Many theories of the fundamental particle interactions predict that massive neutrinos are Majorana in nature. Hence the experiment may establish the Majorana nature, the mass spectrum and the absolute mass scale of the neutrino.

2. The Majorana project
The objective of the first experimental phase of the Majorana Collaboration is to build a 180-kg detector of 86% enriched $^{76}\text{Ge}$ to search for neutrinoless double-beta ($\beta\beta(0\nu)$) decay. This array should reach an ultimate effective Majorana-neutrino mass sensitivity of 100 meV, which is about five times better than current results and covers the quasi-degenerate mass solution region. Our approach is scalable, thus any future desired increases in detector mass to probe smaller neutrino masses can be effectively implemented. The Majorana project is described in detail in [3].

Our proposed experiment uses the well-established technique of searching for $\beta\beta(0\nu)$ in high-purity Ge diode radiation detectors that play both roles of source and detector. The technique is augmented with recent advances in signal processing, detector design, and advances in controlling
intrinsic and external backgrounds. The initial experiment is envisioned to consist of 171 $^{76}\text{Ge}$ crystals in the form of high-resolution intrinsic germanium detectors, deployed in three 57 crystal modules, located deep underground within a low-background shielding environment. This represents more than an order of magnitude increase in the mass of enriched isotope over previous Ge-based experiments. Observation of a sharp peak at the $\beta\beta$ endpoint would quantify the $\beta\beta(0\nu)$ decay rate and provide a measure of the effective Majorana mass of the electron neutrino. The advances in signal processing from segmented Ge-diode detectors offers significant benefits in rejecting backgrounds, reducing sensitivity of the experiment to backgrounds, and providing additional handles on both signals and backgrounds through multi-dimensional event reconstruction. In three years of running it will either conclusively establish the recent claim of double-beta decay [4], or will allow us to significantly improve lifetime limits, from the current level about $2 \times 10^{25}$ years to about $5.5 \times 10^{26}$ years. (See figure [1].)

### 3. Backgrounds

The ideal $\beta\beta(0\nu)$ decay measurement would be background-free. Our goal for Majorana comes close to this ideal in that we aim to achieve a background level in the 4-keV region-of-interest (ROI) window of 1 count/ton/year, a level that provides results very close to those for zero background. This is a formidable challenge. However, based on available technology and our previous experiences in developing low background experiments we believe that it can be attained. Achieving this level also relies on recent technical developments with germanium detectors that should allow us to discriminate and reject a number of potential backgrounds.

It is estimated that the activation rate of $^{68}\text{Ge}$ and $^{60}\text{Co}$ are 1 atom/kg/day on the Earth’s surface and that the detector production process is 100 days. Event reconstruction, pulse shape discrimination and time correlation cuts can greatly reduce the cosmogenic background. We are developing and testing a very low mass support system composed of Cu, plastic, and possibly Si or Ge to reduce the radioactive decays in the inner crystal support structures. Of considerable importance is that we expect to achieve 1 $\mu$Bq/kg of $^{232}\text{Th}$ by chemical manipulation of the electroforming bath. This level of purity is required to ensure this background source is acceptable. Radioactive decays in the copper cryostat that provides vacuum and thermal conductivity to the liquid nitrogen reservoir is also reduced by using the pure electroformed copper.

The total expected background rate is very sensitive to the radio purity of the shield. The reason for this dependence is because of the large mass of the shield itself. We plan to use a layer of electroformed copper as the innermost shield. This will be surrounded by high-quality lead. Small electrical parts that reside close to the detectors inside the shield must also be radiopure. Rn gas within the shield volume will be greatly reduced by purging with boil-off nitrogen.

In addition to material contamination and activation, one must also consider backgrounds from radioactivity from the surrounding rock and from cosmogenic and cosmogenic-induced activity present at the given depth. These backgrounds include primary muons, muon-induced neutrons, and $(\alpha,n)$ neutrons from uranium and thorium decay. Direct muon contributions at 6000 mwe would be more than adequately addressed by a modest muon veto system. Muon-induced neutron backgrounds are addressed by the depth alone. The rock-originating neutrons can be moderated and captured in a plastic layer outside the lead shield.

The potential background from $\beta\beta(2\nu)$ is completely mitigated by the intrinsically good energy resolution of germanium detectors. We estimate that our total background will be near 1 count/ton-year.

### 4. Summary

A 180-kg Majorana detector will allow us to answer several outstanding issues in $\beta\beta$. In three years of running it will either conclusively establish the recent claim of $\beta\beta(0\nu)$ or will allow us to
significantly improve lifetime limits (figure 1). Technical risks in $\beta\beta$ experiments are primarily due to backgrounds, and our pursuit of re-mediation techniques including materials processing, shielding, a deep underground location, excellent energy resolution, pulse shape discrimination, segmentation, granularity, and time correlations - allow us to improve sensitivity and to control risks in the proposed experiment. In addition, if $\beta\beta(0\nu)$ is not observed, it will have provided us with experience and data needed to validate these techniques and to optimize them so that the background can be further decreased in future, larger experiments. Our phased approach is very similar to that proposed in the APS neutrino study [5].

**Figure 1.** Anticipated sensitivity of the proposed 180 kg Majorana experiment. Note: KKDC refers to the positive $\beta\beta(0\nu)$ decay result reported by Klapdor-Kleingrothaus et al [4]. The three arrows indicate the times when each of the three proposed 57-crystal modules start to acquire data.

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