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# Data quality assurance for the MAJORANA DEMONSTRATOR

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**Abstract.** The MAJORANA DEMONSTRATOR is an experiment constructed to search for neutrinoless double-beta decays in germanium-76 and to demonstrate the feasibility to deploy a large-scale experiment in a phased and modular fashion. It consists of two modular arrays of natural and <sup>76</sup>Ge-enriched germanium detectors totalling 44.1 kg, located at the 4850' level of the Sanford Underground Research Facility in Lead, South Dakota, USA. Any neutrinoless double-beta decay search requires a thorough understanding of the background and the signal energy spectra. The various techniques employed to ensure the integrity of the measured spectra are discussed. Data collection is monitored with a thorough set of checks, and subsequent careful analysis is performed to qualify the data for higher level physics analysis. Instrumental background events are tagged for removal, and problematic channels are removed from consideration as necessary.

## 1. Introduction

The process of two neutrino double-beta decay ( $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$ ) is lepton number conserving, and has been observed in multiple isotopes for which a beta decay is energetically forbidden (e.g. <sup>76</sup>Ge, <sup>130</sup>Te, and <sup>136</sup>Xe). However, the process of neutrinoless double-beta decay, ( $(A, Z) \rightarrow (A, Z+2) + 2e^-$ ) violates lepton number conservation, and has not yet been observed. As some theoretical models that give neutrinos mass require lepton number violation, searching for it is therefore of experimental interest.

The main physics purpose of the MAJORANA DEMONSTRATOR [1] is the search for lepton number violation through the process of neutrinoless double-beta decay. While the sum of the energies of the electrons produced in a two neutrino double-beta decay is a continuum, neutrinoless double-beta decay produces electrons with energies summing to the Q-value of the decay (2039 keV for <sup>76</sup>Ge). This results in a signature that can be searched for experimentally, though good energy resolution is important for separating the neutrinoless double-beta decay signal from the irreducible background of the two neutrino double-beta decay spectrum. Ultra-low backgrounds are also important to such a rare event search, as is the ability to scale up to a larger mass detector, to improve the probability of observing a decay in a shorter period of time.

High-purity germanium detectors have a number of advantages for a neutrinoless double-beta decay search. Their excellent energy resolution provides excellent separation between the zero neutrino signal and the two neutrino background. Also, the germanium crystals can be made from material enriched in <sup>76</sup>Ge. This integrates the double-beta decay isotope into the detector active volume without producing any challenges for detector performance.

Therefore, the MAJORANA DEMONSTRATOR has 3 design goals:

- Demonstrating backgrounds low enough to justify building a tonne scale experiment.
- Establishing feasibility to construct and field modular arrays of Ge detectors.
- Searching for additional physics beyond the Standard Model.

The MAJORANA DEMONSTRATOR is currently operating on the 4850' level of the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA. It consists of 2 cryostat modules, each containing 7 strings of 3 to 5 p-type Point-Contact (PPC) germanium crystal detectors. The longer drift time of PPC detectors helps distinguish signal-like single-site interactions from multi-site background interactions. The total mass of the detectors is 44.1 kg,

of which 14.4 kg are natural germanium crystals, and 29.7 kg are enriched to 88%  $^{76}\text{Ge}$ . These cryostat modules are surrounded by copper then lead to shield against gamma rays, active muon veto panels, then polyethylene to shield against neutrons. The boundary between the lead and the muon veto panels is an aluminum enclosure that is sealed and purged with liquid nitrogen boil-off gas to keep radon away from the cryostats. In addition, using radiopure materials in the construction of the experiment was a high priority, in order to achieve the ultra-low backgrounds necessary for such a rare event search [2]. The ultra-low backgrounds of the MAJORANA DEMONSTRATOR, combined with its excellent energy resolution, also make it a multipurpose detector, capable of searching for additional physics beyond the Standard Model [3].

In a rare event search experiment with ultra-low backgrounds, events originating from hardware abnormalities in the detector instrumentation may threaten to dominate the backgrounds for the experiment. Therefore, data quality is monitored during data collection, specific instrumental background event pathologies are identified and either corrected, tagged for removal, or handled in later analysis, and further in-depth analyses performed in order to ensure clean data for physics analysis. The following sections describe these data quality assurance efforts in more detail.

## 2. Monitoring of data collection

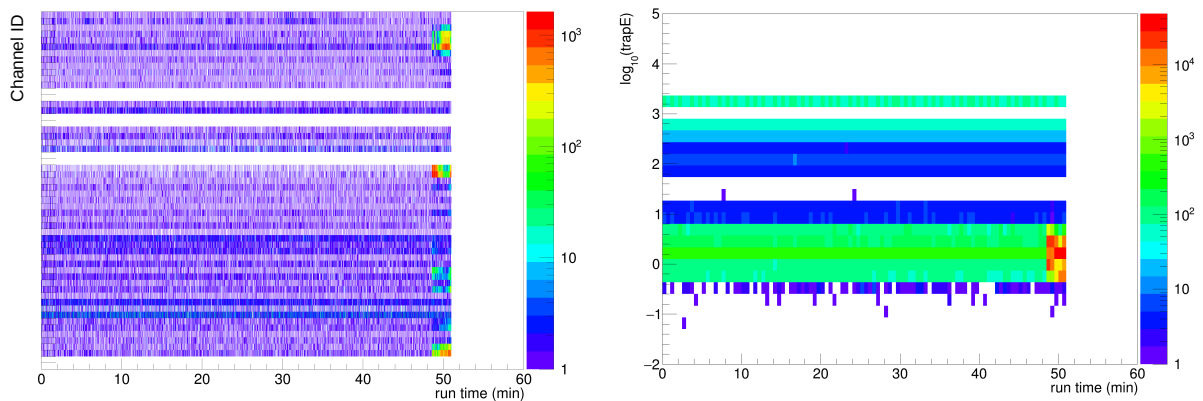
Ensuring good data quality requires continuously being vigilant for problems with the data taking. With this in mind, the interface to the slow controls database (a CouchDB [4] database) contains information on detector conditions in real time. This includes event rates and detector baselines, along with hardware status information (e.g. liquid nitrogen fill levels), and lab environmental conditions (e.g. temperature, humidity, and particulate count). Further processing is also conducted onsite, to allow for near-term monitoring of the data collected.

Once a run is complete ( $\sim 1$  hour during normal data taking) and on the local RAID array, the data is transferred to the Parallel Distributed Systems Facility (PDSF) cluster at the National Energy Research Scientific Computing Center (NERSC), where it is processed within approximately 30 minutes. Metadata for these runs is then uploaded to the run database (also CouchDB). The metadata includes checks of the DAQ configuration and the run conditions as they relate to data quality, such as whether the DAQ system is properly configured for physics running, as well as that there are no indications of other issues. For example, this includes ensuring that the run is long enough, the radon purge rate is sufficient, and the event rate is not too high. This information is combined to assign a rank to the run: gold, silver, bronze, or bad. The run metadata also includes plots that are made of key indicators of detector performance, such as the event rates in each channel, and a coarsely binned energy spectrum as a function of time. The DAQ shifter examines the slow controls and run databases four times per day during normal operations, keeping watch for signs of data quality irregularities in both the live information and the run metadata.

A liquid nitrogen fill is a regular occurrence, and the resulting microphonics are apparent in the run metadata plots. An example is shown in Figure 1.

## 3. Removal of instrumental backgrounds

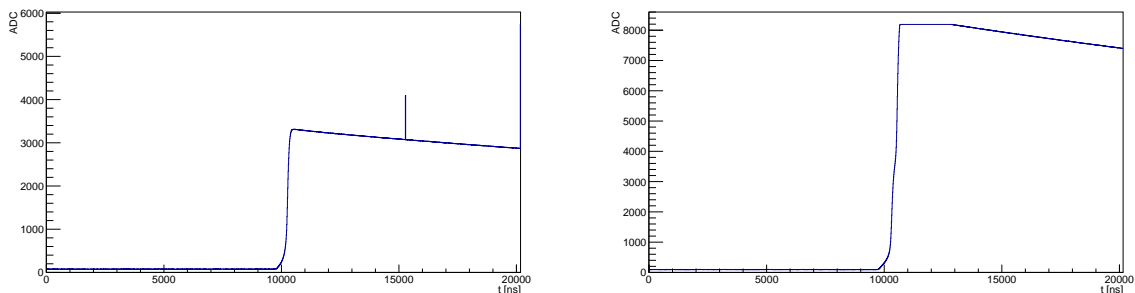
Instrumental backgrounds originate in the electronics used to read out the detectors. This may be due to a hardware abnormality (e.g. a random bit flip in the ADC), but can also be a simple matter of the suitability of the hardware configuration for a given event (e.g. the gain for a channel resulting in a saturated ADC for a high energy event). In some cases, instrumental backgrounds are sufficient to trigger data taking, and result in pure instrumental background events (e.g. triggering on a positive spike on baseline caused by a random bit flip in the ADC). In other cases, an otherwise good physics event may be marred by the presence of an instrumental



**Figure 1.** Channel-by-channel rates (left) and the summed energy (right) as a function of time in a run, from the run database. In the channel-by-channel rates plot, channels are sorted by their position in the module and whether they are the high or low gain channel. A liquid nitrogen fill produced low energy noise at the end of this run.

abnormality (e.g. the positive spike from a random bit flip in the ADC coincides with a physics waveform). This could lead to problems or inaccuracies in the event reconstruction.

Dedicated analyses are performed during waveform reconstruction in order to identify instrumental background waveforms. Once identified, the instrumental background waveforms can either be corrected or tagged so that they can be dealt with properly during the physics analysis. Correcting an instrumental background waveform can involve either removing the pathology added to it by the instrumental background, or replacing the marred waveform with the corresponding waveform in the detector's low gain channel (which may not have the same problem). Two examples of instrumental background waveforms, and how they are dealt with, are shown in Figure 2. To ensure that no unexpected instrumental backgrounds affect the final event sample, a visual scan of waveforms is performed. Ultimately, studies of calibration data and of the measured two neutrino double-beta decay spectrum indicate that instrumental backgrounds affect a very small fraction of physical events (less than 0.1%).



**Figure 2.** Instrumental background waveforms. On the left, a random ADC bit flip caused a spike on the waveform. This is identified and corrected during data processing. On the right, the analog signal exceeded the maximum ADC value. These are tagged for replacement with the detector's low gain channel waveform.

#### 4. Selection of data for physics analysis

The first step in selection of data for physics analysis makes use of the run metadata. The rank in the run database provides a quick way to order runs by their expected data quality, but a final determination on acceptable runs involves considering the run metadata relative to the detector operating conditions, and checking the run metadata plots for any anomalies potentially not captured in the run rank.

Beyond this initial selection of runs, more detailed studies are performed to probe data quality on a run-by-run and channel-by-channel basis. The timing of injected pulses is examined in order to ensure that the channels are synchronized properly. Channels that have insufficient good calibration data to be properly calibrated are flagged for removal. The stability of computed parameters used in the physics analysis (e.g. for removal of multi-site background events) is checked across the dataset, and channels are excluded for runs where detector performance has caused these runs to deviate too far from their nominal values. Finally, periods of anomalously high instrumental background rates are examined, and sufficiently problematic channels are excluded.

Once all of these checks have been performed, the runs and channels that remain are considered to provide data of sufficient quality for physics analysis. During the analysis the tagged instrumental background waveforms are removed, as well as events in periods of time corresponding to a module's liquid nitrogen fills, and any events flagged by the active muon veto. These analysis cuts on the good runs and channels ensure that only high quality data is provided for further physics analysis.

#### 5. Conclusions

The MAJORANA DEMONSTRATOR is a neutrinoless double-beta decay experiment, currently operating on the 4850' level of the Sanford Underground Research Facility. Understanding the signal and background energy spectra is of paramount importance to the experiment, and in this ultra-low background environment, data quality issues could contribute significantly to these spectra. Therefore, between collection of the data and its use for physics analysis are multiple checks of data quality. The outcome of these checks is used to determine which data is of sufficient quality to be analyzed for the neutrinoless double-beta decay search.

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