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A Pulse Shape Analysis technique for the MAJORANA experiment

R.J. Cooper [a,*], D.C. Radford [b], K. Lagergren [a], James F. Colaresi [c], Larry Darken [d], R. Henning [e], M.G. Marino [f], K. Michael Yocum [c]

[a] *Joint Institute for Heavy Ion Research, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6371, USA*
[b] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6371, USA*
[c] *Canberra Industries Inc., 800 Research Parkway, Meriden, CT 06450, USA*
[d] *Canberra Industries Inc., 107 Union Valley Road, Oak Ridge, TN 37830, USA*
[e] *Department of Physics, University of North Carolina, Chapel Hill, NC 27599-3255, USA*
[f] *Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, WA 98195-1560, USA*

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ABSTRACT

In order to achieve background count rates sufficiently low so as to allow the observation of rare events such as neutrinoless double beta ($0\nu\beta\beta$) decay, background suppression techniques are routinely employed. In this paper we present details of a novel Pulse Shape Analysis algorithm, which allows single-site events such as $0\nu\beta\beta$ decay to be distinguished from multi-site background events in germanium detectors. The algorithm, which is based on the event-by-event χ^2 fitting of experimental signals to a basis data set of unique single-site pulse shapes, has been developed through simulation studies and tested experimentally using a Broad Energy Germanium detector. It is found experimentally that the technique is able to successfully identify and reject 99% of multi-site events in the single escape peak associated with the gamma decay of ^{208}Tl, whilst maintaining a survival probability of 98% for neutrinoless double-beta-decay-like double escape peak events.

1. Introduction

The first experimental phase of the MAJORANA project [1] is currently under way—designing and constructing a demonstrator module consisting of 60 kg of High Purity Germanium (HPGe) detectors. The physical goals of this demonstrator, 30 kg of which will be enriched to 86% in ^{76}Ge, are outlined in Ref. [1] and include the realisation of background levels at or below 1 count per tonne year in the $0\nu\beta\beta$ decay region-of-interest ($Q_{\beta\beta}$, from ^{76}Ge = 2039 keV). While the demonstrator will be deployed deep underground, housed in a low background shielding environment, and is being carefully designed so as to minimise external background, the use of background rejection techniques during data analysis remains essential if this goal is to be achieved.

In the 4 keV-wide region-of-interest around 2039 keV it is expected that the main source of background will arise from gamma rays, likely to interact through multiple energy depositions via the Compton scattering process. As the $0\nu\beta\beta$ events of interest are essentially single-site events, having very localised energy deposition profiles, techniques that allow multi-site events to be identified and vetoed may result in large gains in sensitivity through the reduction of background.

As the MAJORANA DEMONSTRATOR will comprise about 100 individual HPGe detectors with a total mass of 60 kg, one simple approach is to apply a so-called 'granularity cut', where the detectors in the array are operated in anti-coincidence mode. Beyond this, for events confined to an individual crystal, it is necessary to study the pulse shape response or segment the detector's outer contact[1] in order to determine the nature of the interaction. Various Pulse Shape Analysis (PSA) algorithms, based on techniques such as neural networks [2], signal parameterisation [3–5] and segmentation schemes [6,7] have been developed and employed in previous $0\nu\beta\beta$ experiments.

Here we present a PSA technique for the MAJORANA project. Simulations have been performed in order to assess the feasibility of this approach while experimental measurements have been made to quantify the background rejection efficacy.

2. Pulse Shape Analysis with point contact detectors

The HPGe detectors integrated into the MAJORANA DEMONSTRATOR will be of p-type Point Contact (PPC) design [4]. These detectors, described as 'shaped field germanium detectors' in

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* Corresponding author.
E-mail address: cooperrj@ornl.gov (R.J. Cooper).

[1] This approach is not favoured by the MAJORANA DEMONSTRATOR due to the increased background arising from the need to instrument multiple channels per detector.

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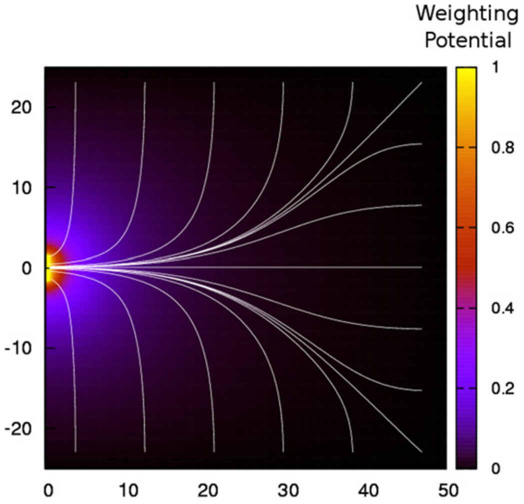

Fig. 1. Schematic representation of two-dimensional slice through a generic 50 mm × 50 mm PPC detector. The weighting potential associated with the 5 mm diameter point contact is displayed as an intensity map while the white lines show the drift paths associated with holes generated at various interaction positions throughout the crystal. The *x* and *y* axes show the longitudinal and radial dimensions of the crystal in mm, respectively.

Ref. [8], are large volume, p-type, cylindrical HPGe crystals with a wrap around n$^+$ outer contact and p$^+$ point contact from which the signal is read out. This point contact geometry not only serves to minimise series noise through a reduction of capacitance [8], but also offers charge collection and signal induction characteristics ideally suited for the task of identifying multi-site events. Fig. 1 shows a representation of a generic 50 mm × 50 mm PPC detector with a 5 mm diameter point contact. The weighting potential [9] associated with the point contact has been calculated and overlaid as an intensity map along with the charge-carrier-drift trajectories associated with interaction positions throughout the crystal. This figure shows how the weighting potential, which describes the position-dependent electrostatic coupling between charge carrier and contact, falls off quickly, resulting in the induction of a significant signal only when charge carriers are in close proximity to the point contact. As such, detectors of this design essentially operate as single-charge sensing devices. For interactions occurring throughout the majority of the active volume, only the charge carriers that drift towards the point contact (in this case the positively charged holes) make a significant contribution to the signal.

The combination of long drift distances and sharp increase in weighting potential close to the point contact gives rise to a large, fast current pulse associated with each interaction. This in turn results in a preamplifier charge signal that is characterised by a slow initial rise as the holes drift in the region of low weighting potential, followed by a steep rise to a maximum at the end of the charge collection process. Fig. 2(b) shows an experimental example of a charge-pulse, recorded following a single-site event in a PPC geometry detector, while the corresponding current-pulse, obtained through differentiation of the charge signal in a Timing Filter Amplifier (TFA), can be seen in Fig. 2(a). As the current signal induced by a multi-site event is essentially a linear superposition of two or more individual current pulses, one observes a current and charge pulse response typical of that displayed in Fig. 2(c) and (d). The clear difference in pulse shape response observed for multi-site events relative to single-site interactions serves to illustrate how the characteristics of the PPC detector geometry lend themselves to background rejection through PSA techniques.

A further consequence of the small electrode effect [10] that governs signal generation within a PPC detector is that, with the exception of the small fraction of events for which interaction occurs close to the point contact, for single-site events almost no variation in signal shape exists. Rather, the location of interaction affects only the delay with which the signal begins to rise.

Our PSA algorithm is based on the event-by-event comparison of recorded waveforms to a database of signals representing all possible pulse shapes that may result from single-site interactions throughout the crystal volume. By performing χ^2 comparisons between the recorded signal (the candidate signal) and the database signals (the 'basis' signals) the algorithm evaluates the

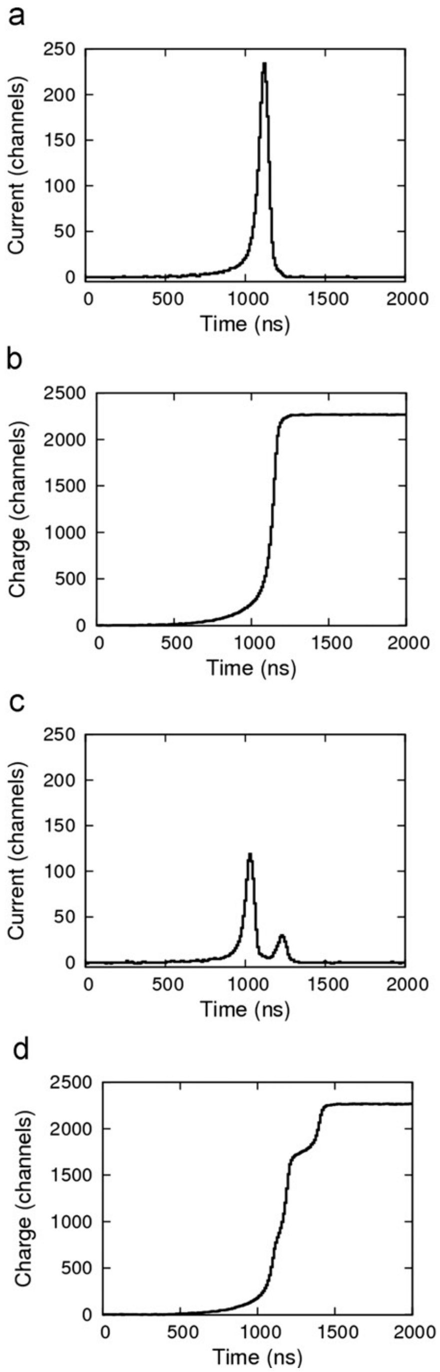

Fig. 2. Current and charge pulse response of a PPC geometry detector to single- and multi-site gamma-ray events. The pulse shapes in (a) and (b) show the current and charge signals resulting from a typical single-site interaction while (c) and (d) show how the pulse shape response to a multi-site interaction is clearly different. The signals in all four panels resulted from the full absorption peak of 1332 keV gamma rays.