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# New Opportunities in Decay Spectroscopy with the GRIFFIN and DESCANT Arrays

V. Bildstein[a], C. Andreoiu[d], G.C. Ball[e], T. Ballast[e], C. Bartlett[e], P.C. Bender[e], N. Bernier[e], L. Bianco[a,b], D. Bishop[e], D. Brennan[e], T. Bruhn[e], A. Cheeseman[e], R. Churchman[e], S. Ciccone[e], B. Davids[e], G. Demand[a], I. Dillmann[e], A.B. Garnsworthy[e], P.E. Garrett[a], S. Georges[e], G. Hackman[e], B. Hadinia[a], R. Kokke[e], R. Krücken[e], Y. Linn[e], C. Lim[e], J-P. Martin[f], D. Miller[e], W.J. Mills[e], L.N. Morrison[e], C.A. Ohlmann[e], J. Park[e], C.J. Pearson[e], J.L. Pore[d], M.M. Rajabali[e], E.T. Rand[a], U. Rizwan[d], F. Sarazin[g], B. Shaw[e], K. Starosta[d], C.E. Svensson[a], C. Sumithrarachchi[a,c], C. Unsworth[e], P. Voss[d], Z.M. Wang[e], J. Williams[d], J. Wong[a], S. Wong[e1]

[a]*Physics Department, University of Guelph, 50 Stone Rd E, Guelph, ON, N1G 2W1, Canada*
[b]*DESY, Notkestr. 85, 22607 Hamburg, Germany*
[c]*NSCL, 640 S. Shaw Ln, East Lansing, Michigan 48824-1321, USA*
[d]*Department of Chemistry, Simon Fraser University, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada*
[e]*TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada*
[f]*Département de physique, Université de Montréal, PO Box 6128, Montréal, QC, H3C 3J7, Canada*
[g]*Department of Physics, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, USA*

**Abstract**

The GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei) project is a major upgrade of the decay spectroscopy capabilities at TRIUMF-ISAC. GRIFFIN will replace the 8π spectrometer with an array of up to 16 large-volume HPGe clover detectors and use a state-of-the-art digital data acquisition system. The existing ancillary detector systems that had been developed for 8π, such as the SCEPTAR array for β-tagging, PACES for high-resolution internal conversion electron spectroscopy, and the DANTE array of LaBr3/BaF2 scintillators for fast γ-ray timing, will be used with GRIFFIN. GRIFFIN can also accommodate the new neutron detector array DESCANT (Deuterated Scintillator Array for Neutron Tagging), enabling the study of β-delayed neutron emitters. DESCANT consists of up to 70 detectors, each filled with approximately 2 liters of deuterated benzene, a liquid scintillator that provides pulse-shape discrimination (PSD) capabilities to distinguish between neutrons and γ-rays interacting with the detector. In addition, the anisotropic nature of n-d scattering as compared to the isotropic n-p scattering allows for the determination of the neutron energy spectrum directly from the pulse-height spectrum, complementing the time-of-flight (TOF) information. The installation of GRIFFIN

* Corresponding author. Tel.: +1-519-824-4120; fax: +1-519-836-9967.
*E-mail address:* vbildste@uoguelph.ca

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is under way and first experiments are planned for the fall of 2014. The array will be completed in 2015 with the full complement of 16 clovers. DESCANT will be tested coupled with GRIFFIN in spring of 2015.

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*Keywords:* Gamma-ray spectroscopy; Beta decay; Beta-delayed neutron emission; HPGe clover detectors; Deuterated Benzene Neutron Detectors

## 1. Introduction

Spectroscopy following β-decay is an important tool in studying radioactive isotopes. In a β+/β--decay one can observe, besides the β-particles, γ-rays and conversion electrons from the de-excitation of the daughter nuclei. With the 8π spectrometer located at TRIUMF-ISAC (Dilling et al. (2014)), as described in Garnsworthy and Garrett (2014), high-intensity beams close to stability have been studied with beam intensities of up to 108 ions per second, yielding high-statistics data sets that probed very weak decay branches, e.g. Garrett et al. (2012), as well as low-intensity beams far from stability with rates of a few ions per second, e.g. Mattoon et al. (2007). The new GRIFFIN array with its much higher efficiency will allow even weaker branches or nuclei even further from stability to be studied.

In cases where the Q-value of the reaction is larger than the one-neutron-separation energy, Sn, β-delayed neutron emission can occur (1n-branch). The probability of the emission of a neutron increases with the Q - Sn value. In cases where the Q-value of the reaction is even larger, the emission of two, three, or even four neutrons is also possible. These β-delayed neutrons play an important role in the stable operation of nuclear reactors, contribute to the decay heat of spent nuclear fuel, influence the abundance pattern of the astrophysical r-process, and yield information about the nuclear structure of the daughter nuclei.

Despite the importance of β-delayed neutron data, only about 50% of the 1n branching ratios have been measured, and much fewer of the 2n, 3n, or 4n branching ratios, as reported in the first research coordination meeting of the IAEA CRP on β-delayed neutron emission evaluation. Due to the intrinsic difficulty of measuring these branching ratios, calculations such as Möller et al. (2003) , the available data can differ up to an order of magnitude between different measurements. The new DESCANT (DEuterated SCintillator Array for Neutron Tagging) array will provide a high efficiency to detect β-delayed neutrons, contributing to our understanding of this important process, and its coupling to GRIFFIN will enable n-γ coincidence studies.

## 2. GRIFFIN

The GRIFFIN array (see also Svensson and Garnsworthy (2014)) comprises 16 unsegmented clover detectors, each with four 90 mm long, approximately 40% relative efficiency, high-purity germanium (HPGe) crystals. The array has the same geometry as the segmented TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) array (see Hackman and Svensson (2014)) tapered for close-packing. The design also includes mounting options for the bismuth germanate (BGO) suppression shielding of the detectors. The detectors will fill 16 of 18 faces of a rhombicuboctahedron with the remaining faces used for the beam entry and the tape-system. The triangular gaps between detectors are available to mount fast-timing $BaF_2$ or $LaBr_3$ detectors, also designed to accommodate BGO suppression shields.

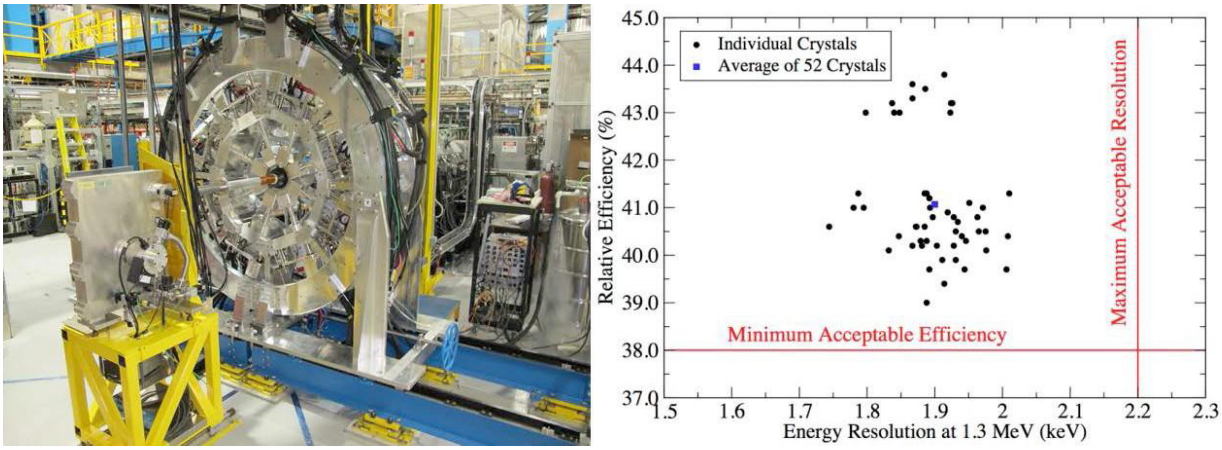


Figure 1: On the left a picture of the GRIFFIN array as of July 18th, 2014. Eight HPGe clover detectors are mounted around the target chamber and the tape system can be seen in the foreground. On the right the energy resolution and relative efficiency at 1.3 MeV of the thirteen fully accepted GRIFFIN detectors is shown. On average the 52 crystals had an energy resolution of 1.1 keV at 121 keV and 1.9 keV at 1.3 MeV. The average relative photo-peak efficiency of the crystals is 41.1% at 1.3 MeV.

The existing in-vacuum ancillary detectors of the $8\pi$, namely the 20 plastic scintillators $\beta$ detectors of SCEPTAR (SCintillating Electron-Positron Tagging Array), the 5 Si(Li) conversion electron detectors of PACES (Pentagonal Array of Conversion Electron Spectrometers), and the zero degree scintillator (ZDS) $\beta$ detector , will all be available for use with GRIFFIN.

### *2.1. Data acquisition system*

The data acquisition system for GRIFFIN will use state-of-the-art digital electronics to allow rates of up to 300 MB/s of filtered data to be written to disk, while maintaining the ability to perform high-precision super-allowed $\beta$-decay studies as is required, for example, in the Fermi superallowed $\beta$-decay program. The front-end electronics will use 14 bit 100 MHz sampling ADCs for the energy signals of the HPGe, Si(Li), and LaBr3 detectors. The 20 plastic scintillating $\beta$ detectors, the DESCANT detectors, and the fast-timing signals of the LaBr3 detectors will be read out at 1 GHz with 12 bit resolution. The data from the front-ends is processed in two levels of collector modules that run filtering algorithms and pass the data to be written to disk. All modules are synchronized by a single centralized clock-module that uses a chip-sized atomic clock to generate a precise 10 MHz reference signal. The tape-system and the electrostatic beam kicker will be controlled by the master control module via a programmable pulse generator (PPG) module.

### *2.2. Status*

To date, 13 of the 16 clover detectors have been received by TRIUMF with acceptance tests at Simon Fraser University. All detectors have had energy resolutions and relative efficiencies surpassing the requirements with an average relative photo-peak efficiency of 41.1% at 1.3 MeV and energy resolutions of 1.1 keV and 1.9 keV at 121 keV and 1.3 MeV, respectively, as shown on the right of Fig. 1. The beam line and the electronics shack have been installed and the support structure for the HPGe detectors has been put in place. As of July 18th, 2014, eight HPGe clover detectors have been mounted and aligned (see the left of Fig. 1) and are being used to test the new digital DAQ. GRIFFIN is scheduled to take first radioactive beam in September of 2014. Since the photopeak efficiency of GRIFFIN is more than a factor 17 higher than the photopeak efficiency of the $8\pi$ at 1 MeV, the $\gamma\gamma$-efficiency (which is the square of the photopeak efficiency) will be about a factor 300 higher than that of 8π. This will greatly enhance the decay spectroscopy abilities at TRIUMF.

At present, a number of experiments have been approved by TRIUMFs Experiments Evaluation Committee (EEC). A repeat of the study of $^{32}$Mg via the β-decay of $^{32}$Na (Mattoon et al. (2007)) will take advantage of the higher γγ-efficiency of GRIFFIN to study the spin of excited states via the angular correlations of the emitted γ-rays. A high-precision measurement of the *ft* value of $^{35}$Ar will be performed at TRIUMF. It will use the GRIFFIN array to obtain the branching ratio together with mass measurements from TITAN (Kwiatkowski et al. (2014)) and a high-precision half-life measurement with GPS 4π gas-counter (Ball (2014)). The measurement of the *ft* value will provide a measurement of $V_{ud}$, competitive to that obtained by super-allowed Fermi β-decays. Also part of the program on high-precision super-allowed β-decay studies is an experiment on the β+-decay of $^{62}$Ga. An experiment to search for a 4p-6h "super-intruder" band in $^{110,112}$Cd has also been approved. A number of other letters of intent have already been endorsed by the EEC and are awaiting development of the beams required.

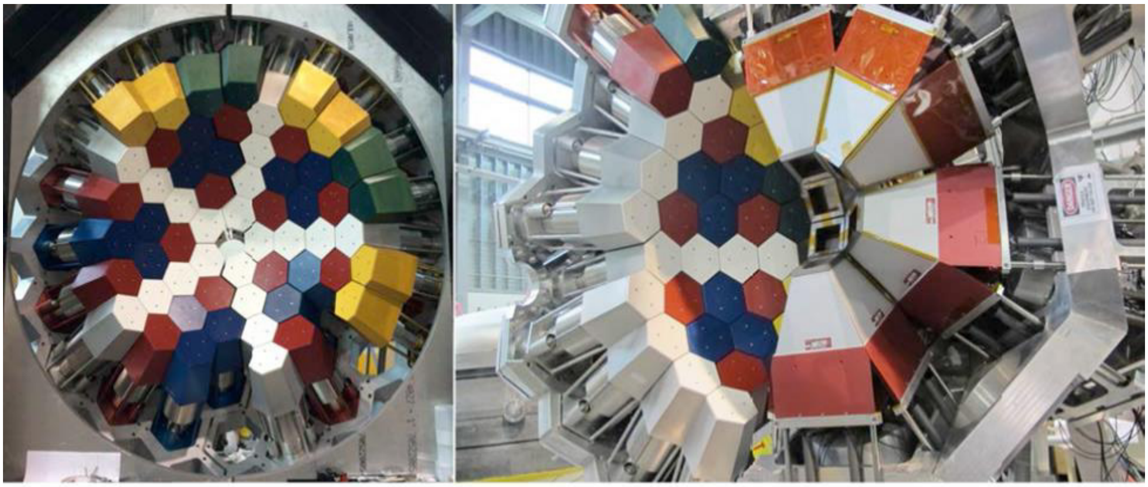

Figure 2: The DESCANT detectors mounted on the assembly stand on the left and one half of DESCANT mounted on the TIGRESS array.

## 3. DESCANT

The 70 close-packed detectors of DESCANT (see also Garrett (2014)), filled with ≈ 2 liters of deuterated Benzene (BC-537). DESCANT can be mounted onto the GRIFFIN frame, replacing the four downstream HPGe detectors. In this configuration DESCANT covers 1.08 π of the solid angle. The distance between the implantation point and the front faces of the detectors is 50 cm and the detectors are 15 cm thick. This ΔL/L of 30% will limit the energy resolution achievable by the time-of-flight (TOF) technique, however, the anisotropic nature of the *n-d* scattering will allow the determination of the neutron energy spectrum directly from the pulse-height spectrum, an unfolding technique (see Ojaruega et al. (2011)). This technique will perform best for high neutron energies where the background from other neutron energies is low. A combination of the energy and time-of-flight data using an unfolding technique on the two-dimensional spectra will be investigated to achieve an energy resolution better than 30% without losing the high efficiency this setup guarantees.

### 3.1. Digital data acquisition and firmware

The digital electronics used to read out the DESCANT detectors was built at the Université de Montréal. The modules are capable of digitizing the anode signal of the photomultiplier tubes (PMTs) at up to 1 GHz with 12 bit resolution. Currently the cards are being run at 800 MHz while the field programmable gate array (FPGA) that processes the data runs at 100 MHz. This means that at each clock cycle of the FPGA eight ADC data words have to be processed in parallel, which increases the amount of resources needed on the FGPA by roughly a factor eight as well. The firmware for the analysis of the anode signals is being developed at the University of Guelph with the goal to perform onboard timing, energy determination, and pulse-shape discrimination (PSD). The timing algorithm is an implementation of an analogue constant fraction discriminator (CFD), using a linear interpolation between samples to determine the zero crossing of the monitor signal, see Figure 3, though this might be changed to a cubic interpolation. The energy is determined via a simple moving window integration. For the PSD three algorithms will be implemented: i) a charge-charge comparison (CC) algorithm comparing the integral of the tail of the signal and the integral of the whole signal, ii) a time-to-zero-cross-over (TZC) algorithm comparing the start of the signal (from the CFD algorithm) with the time at which the integrated signal has reached a certain percentage of the whole integral, and iii) a pulse gradient analysis (PGA) algorithm that uses the normalized difference between a sample in the peak of the signal and a sample in the tail of the signal.

The combination of all three algorithms will allow the use of offline multi-dimensional cuts to separate neutron events from γ-ray events, with further input of the constraint of the ToF data.

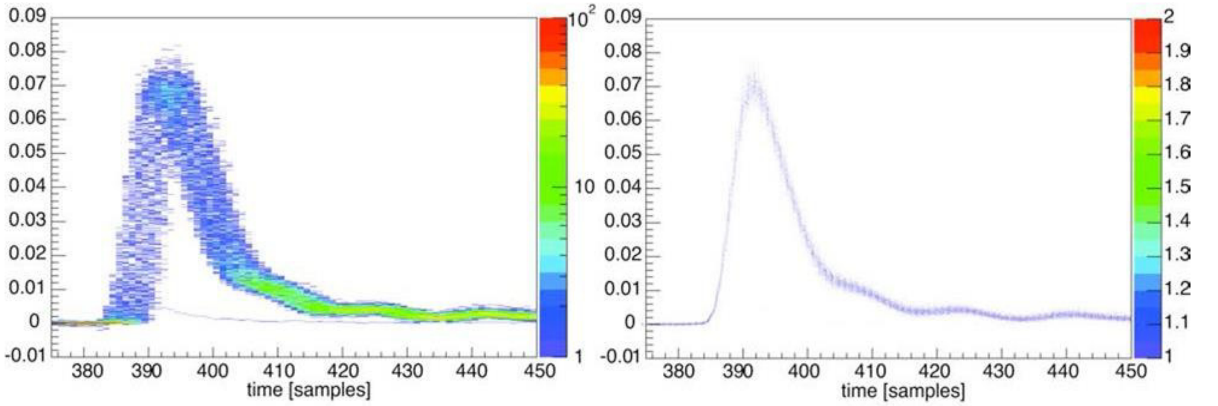


Figure 3: Waveforms collected by a DESCANT detector with a $^{137}$Cs source in front of it connected to a 4G digitizer card. All waveforms are background corrected by the card and normalized. The timing of the waveforms is "as is" on the left and corrected by the on-board linear interpolation between the last positive and first negative sample of a CFD monitor signal.

### 3.2. Status

All 70 DESCANT detectors plus two spare detectors have been delivered and were accepted after they were tested at the University of Guelph. The majority of the detectors have been shipped to TRIUMF and are mounted on an assembly stand, see Fig. 2. The design of the front-end digitizer cards has been finalized and the algorithms for on-board determination of the timing and energy have been implemented in firmware. The algorithms for the pulse-shape discrimination of neutrons and γ-rays are being developed at the University of Guelph. DESCANT will be ready for the experiments with GRIFFIN in 2015.

## 4. Summary

The new HPGe array GRIFFIN will provide state-of-the-art β-decay spectroscopy with a factor 300 greater efficiency for γγ-coincidences than the previous 8π array. The installation and testing of GRIFFIN is proceeding as planned and radioactive beam will be sent to the array in September 2014.

The DESCANT neutron detector array can be coupled with GRIFFIN, providing high-efficiency neutron detection. This will be used to study β-delayed neutron emission, contributing to our understanding of the astrophysical r-process, nuclear reactor safety, and stockpile stewardship. A wide ranging program of study of β-delayed neutron emitters with n-β-γ coincidences is envisioned.

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