EXPLORING EXOTIC NUCLEI WITH THE GRIFFIN SPECTROMETER AT TRIUMF-ISAC*

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The new GRIFFIN gamma-ray spectrometer has replaced the 8π spectrometer as a dedicated facility for decay spectroscopy experiments at TRIUMF-ISAC. This facility enables a broad program of research in the fields of nuclear structure, nuclear astrophysics and fundamental symmetries using stopped radioactive beams. In this contribution, an overview is given of the detector systems with examples of the experiments performed with the device during the first year of operation at ISAC.

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1. Introduction

The TRIUMF-ISAC facility [1] in Vancouver, Canada uses the isotope separation on-line (ISOL) technique to produce high-quality beams of radioactive ions. The primary ISOL targets are bombarded by a 500 MeV beam of protons from the TRIUMF 18 meter diameter main cyclotron with an intensity of up to 100 microamps. Low-energy ($\sim$ 20–60 keV) beams of radioactive isotopes with masses up to $A = 238$ can be transported directly to a variety of experiments in the low-energy area of ISAC, including the new GRIFFIN facility [2] dedicated to decay spectroscopy studies. GRIFFIN has replaced the 8π facility [3–5] that served as the primary facility for decay spectroscopy research at ISAC-I for the past decade and represents a dramatic increase in detection efficiency.

The Advanced Rare IsotopE Laboratory (ARIEL) [6] project is currently under construction at TRIUMF and will provide simultaneous multi-user radioactive beam capability to the ISAC experiments. High intensity beams of neutron-rich radioactive beams will be delivered from actinide production

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targets driven by both a new superconducting electron linear accelerator and a second 500 MeV proton beamline from the TRIUMF main cyclotron. Along with other experimental facilities operational at ISAC, GRIFFIN will play an important role in fully exploiting the opportunities for nuclear structure, nuclear astrophysics, and fundamental symmetries research that will be provided by ISAC and ARIEL.

2. Description of the facility

GRIFFIN, pictured in Fig. 1, is comprised of sixteen high-purity germanium (HPGe) clover detectors arranged into a close-packed array. Sixteen of the eighteen square faces of a rhombicuboctahedron are covered by HPGe at a source-to-detector distance of 11 cm. One of the remaining square faces is used for the delivery of the low-energy radioactive ion beam from TRIUMF-ISAC-I and the final square is used for the in-vacuum moving tape collector system to remove long-lived activity from the chamber at the end of a measurement cycle. This detector arrangement is in a similar geometry to the TIGRESS spectrometer [7, 8] operating in the ISAC-II experimental hall.

The HPGe clovers each contain four 90 mm long, n-type crystals in a common cryostat. Detailed initial acceptance testing of each detector was performed by members of the collaboration at Simon Fraser University. The detectors have demonstrated excellent performance with a relative efficiency of $> 40\%$ and energy resolution of < 2 keV at 1.3 MeV averaged over all 64 crystals.

The primary ancillary detector system used in the GRIFFIN facility is the Scintillating Electron Positron Tagging Array (SCEPTAR) consisting of 20 plastic scintillators located inside the vacuum chamber [4]. These detectors subtend roughly 80% of the solid angle and are used to tag on beta particles emitted in the decay of a parent nucleus and provide a reduction of the gamma-ray random room background observed in spectra by many orders of magnitude.

The gap between the inner vacuum chamber and the GRIFFIN HPGe detectors can optionally be filled by spherical shells of Delrin with a thickness up to 20 mm. The purpose of this low-Z absorber is to stop energetic beta particles from reaching the HPGe detectors, while minimizing bremsstrahlung production. The use of this absorber affects the gamma-ray efficiency at low energies in a negative way but the reduction in background is often of more benefit in the study of high-Q-value beta decays.

The other ancillary detector systems previously developed for use with the 8π spectrometer will also be used with GRIFFIN. In the vacuum chamber, this includes the five liquid nitrogen cooled lithium-drifted silicon conversion electron detectors of the Pentagonal Array of Conversion Electron

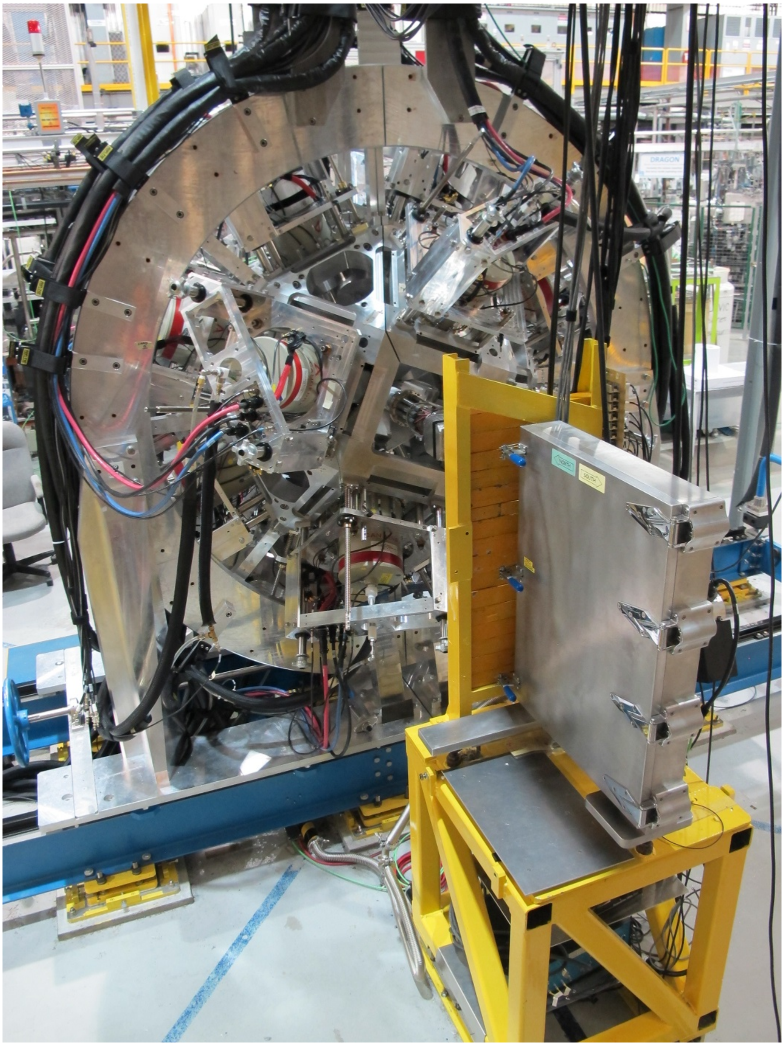

Fig. 1. Photograph of the GRIFFIN spectrometer installed at TRIUMF-ISAC-I.

Spectrometer (PACES). The rhombicuboctahedron geometry provides an additional 8 triangular faces which can be used for ancillary detectors. The primary ancillary detector which will be employed in the future is a set of $LaBr_3$ scinitillators for fast-coincidence-timing measurements of gamma rays.

In addition to these systems which were developed for use with the 8π spectrometer, it will also be possible to couple the new 70-element Deuterated Scintillator Array for Neutron Tagging (DESCANT) [9, 10] neutron detector array to GRIFFIN by removing the four downstream HPGe clover detectors. This combination of GRIFFIN and DESCANT will provide a powerful setup for beta-delayed neutron-gamma coincidence detection capability.

It is planned to implement a full set of modular bismuth germanate (BGO) Compton and background suppression shields of a similar design to those used in the TIGRESS array [11] over the next several years.

3. Data acquisition system

The data acquisition (DAQ) system for GRIFFIN has been custom designed and builds on experience in operating the digital electronics of the TIGRESS DAQ system [12] and the 8π analogue DAQ system. The primary design features for the system are to facilitate the two main requirements of the physics program for nuclear structure and precision measurements: to enable high-counting and data-collection rates with each HPGe crystal operating at 50 kHz, and to achieve a level of accountability and dead-time/pile-up/event traceability which allows precision half-life or branching ratio measurements to be made to a level of $< 0.05\%$. Every module and piece of firmware in the system was designed with these concepts in mind by collaborators at TRIUMF and Université de Montréal. Initial signal processing is performed with a 14-bit, 100 MHz front-end digitizer examining the output signal of charge-sensitive preamplifiers connected to HPGe and plastic scintillators. A digitizer sampling at 14-bit, 1 GHz is also in development to process the signals from scintillator photomultiplier tubes directly without the need for a preamplifier. All events are pushed forward to FPGA filtering logic where user-selectable coincidence conditions must be satisfied before the data is committed to data storage.

4. Experimental studies performed with GRIFFIN

First experiments were completed with an early-implementation of the GRIFFIN facility during the final few months of 2014. Further experiments have been performed in 2015 with the full complement of detectors and digital electronics.

The first experimental beamtime using GRIFFIN aims to examine the competition between different astrophysical production mechanisms of ^{116}Cd through a detailed study of the excited states in ^{115}Cd [13]. It is established that the isotope ^{116}Cd can be produced from the astrophysical rapid-neutron-capture process but the contribution, if any, from the slow-neutron-capture process is more questionable. The ground state of ^{115}Cd has a half life of just 53.46(5) hrs and so in an astrophysical environment will beta-decay to ^{115}In. However, a much longer-lived isomeric state with a half life of 44.56(24) days exists in ^{115}Cd which, if populated, would provide an avenue for neutron-capture to ^{116}Cd. This spin-trap isomeric state at 181 keV excitation energy would only be populated in an astrophysical environment if it were in thermal equilibrium with the ground state through population in (γ, γ') reactions. This will certainly be the case in high-temperature astrophysical environments but if this were to be true at lower temperatures, then doorway states and transitions must be present at low excitation energy. A candidate for such a gateway transition is an E1 transition of 33 keV connecting the states at 394 and 361 keV. GRIFFIN will be used to determine the strength of this E1 transition through coincidence gating of transitions above and below these states.

The beam provided by ISAC was of excellent quality due to the ability of the TRIUMF-Laser-Ion-Source (TRILIS) to separately resonantly-ionize the ground state ($T_{1/2} = 20$ mins) and the isomeric state ($T_{1/2} = 18$ secs) of ^{115}Ag. Figure 2 clearly shows the difference in the gamma-ray spectra when $A = 115$ beams were delivered to the GRIFFIN spectrometer with various

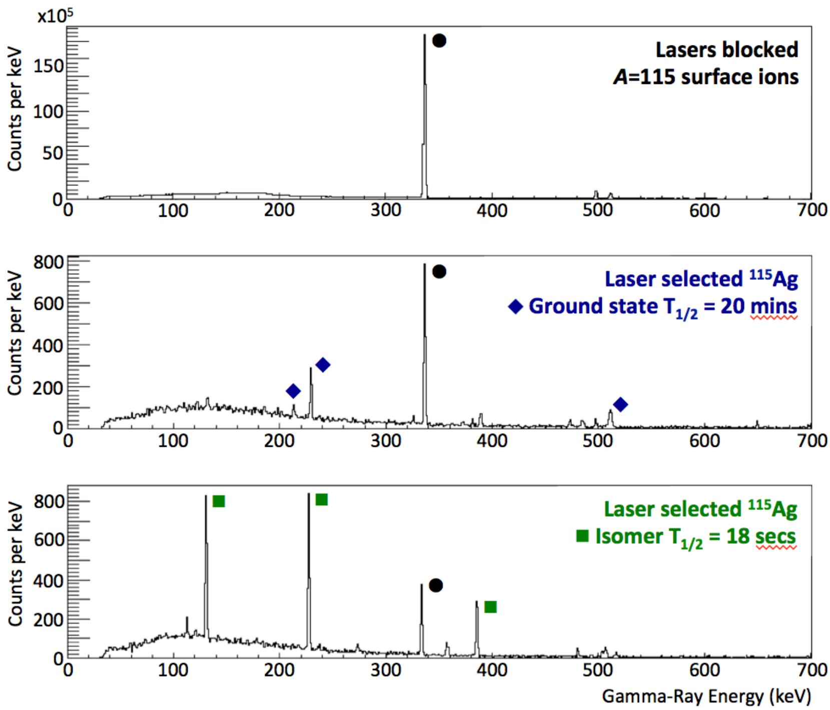

Fig. 2. Gamma-ray singles spectra of a $A = 115$ beam observed by GRIFFIN for three different laser settings; lasers blocked, laser tuned to the ^{115}Ag ground state resonance, laser tuned to the ^{115}Ag isomeric state resonance.

settings of the TRILIS lasers. When the lasers were blocked completely, only surface ions are observed which was primarily the isomeric state in ^{115}In ($T_{1/2} = 4.5$ hrs) which decays by a 336 keV gamma ray. This surface-ionization background is also present when the lasers are used. With the lasers tuned to selectively ionize the ^{115}Ag isomeric state then an intensity of $\sim 30,000$ pps of the isomeric state was delivered to GRIFFIN. When the lasers were instead tuned to selectively ionize the ^{115}Ag ground state, the intensity was $\sim 8,000$ pps with a contribution of ~ 80 pps of the ^{115}Ag isomeric state remaining in the beam. Detailed analysis of the data from all beam modes are now underway.

The GRIFFIN spectrometer has been used for high-statistics beta decay studies of ^{46}Ca and ^{47}Ca using radioactive beams of K isotopes. The neutron-rich calcium isotopes have been a primary testing ground of modern theoretical calculations of nuclear structure. A detailed study of the excited states in these calcium isotopes can help scrutinize the accuracy of these calculations, especially for hole states in the $f_{7/2}$ orbital and the influence of proton core-excitations. The high gamma–gamma coincidence efficiency and geometrical symmetry of the GRIFFIN detectors makes the device well-suited to performing gamma–gamma angular correlation measurements to determine the spins of excited states. Figure 3 shows the relative intensities of coincident gamma-rays in ^{47}Ca at 50 of the 52 unique angles in the GRIFFIN spectrometer. The 2013 keV E2 transition populates the $J^{\pi} = 7/2^{-}$ ground state from the 2013 keV, $3/2^{-}$ excited state. The E1 transitions of 586 and 565 keV feed the 2013 keV state by depopulating states of $1/2^{+}$ and $3/2^{+}$ respectively which result in gamma–gamma angular correlations with very different shapes. Figure 3 shows that the experimental data are in excellent agreement with the expected theoretical distributions for these cascades [14, 15]. In these examples, there are millions of coincidences included in the data so the intensity at 50 of the 52 unique angles between different HPGe crystals is shown. With lower statistics, the angles can be grouped together and the plot folded to take advantage of the symmetry of the detector positions and the angular distribution. Geant4 simulations performed by the GRIFFIN Collaboration indicate that gamma–gamma correlation measurements will be possible when just a few thousand coincidences are collected.

The island of inversion has been the subject of intense study since an unexpectedly large deformation was first suggested in the $N = 20$ isotope, ^{32}Mg. It is now established that this region of deformation is brought about by particle-hole excitations across the $N = 20$ shell closure and a reduction in the size of the gap by the $T = 0$ attractive monopole tensor interaction [17, 18]. Several beta-decay studies of the excited states in ^{32}Mg have been performed previously with the most comprehensive being by Tri-

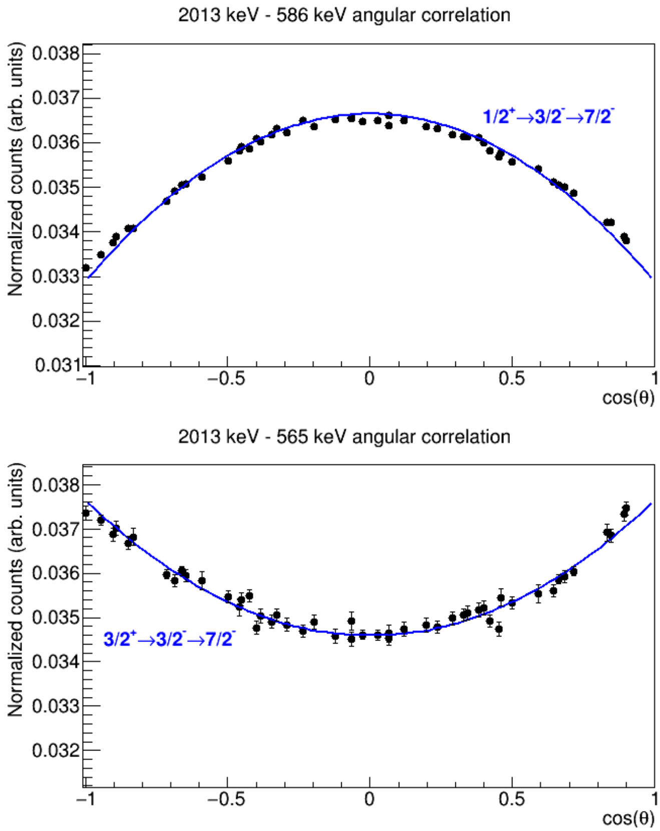

Fig. 3. Gamma–gamma angular correlations following the β-decay of ^{47}K to ^{47}Ca measured using 50 of the 52 unique angles of the GRIFFIN spectrometer. The line represents the theoretical distribution for each cascade.

pathi *et al.* at NSCL and by Mattoon *et al.* using the 8π spectrometer at TRIUMF-ISAC [16]. Similar results were observed in both of these most recent studies. A new study of the beta decay of ^{32}Na has been performed using the GRIFFIN spectrometer. The spectrum of gamma rays observed in coincidence with the 885 keV $2_1^+ \rightarrow 0^+$ transition in ^{32}Mg is shown in figure 4 comparing the data from the previous 8π experiment and a portion of the data collected with GRIFFIN. The level of statistics collected with GRIFFIN is expected to be sufficient to make a spin/parity assignment to the majority, if not all, the excited states observed in beta decay.

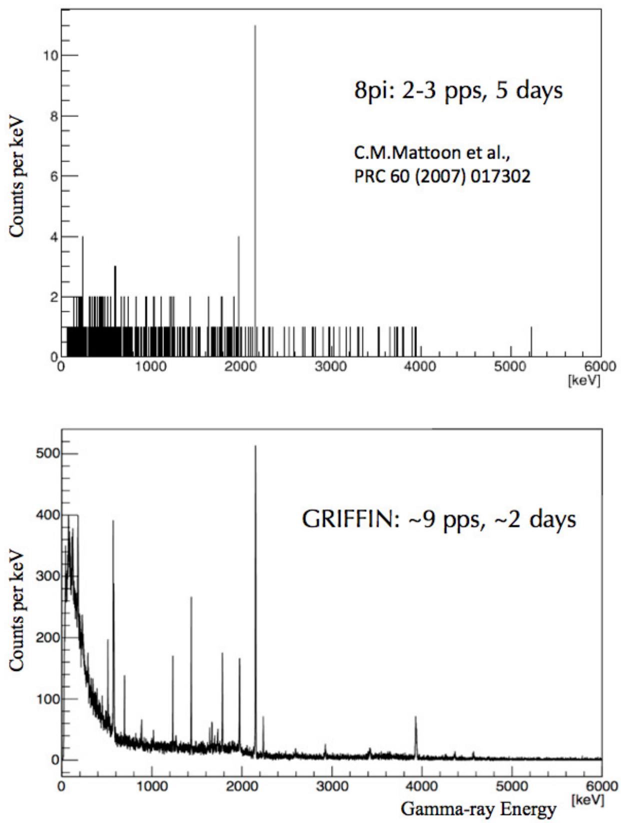

Fig. 4. Gamma-rays seen by the 8π and GRIFFIN spectrometers in coincidence with the $2^+ \to 0^+$ transition in ^{32}Mg following the β-decay of ^{32}Na. The 8π spectrum in the upper panel is taken from Ref. [16].

5. Outlook

The GRIFFIN facility greatly enhances the capabilities in decay spectroscopy at ISAC through a combination of an increase in gamma–gamma efficiency over the 8π spectrometer by a factor of ~ 300, and the development of a state-of-the-art digital data acquisition system. GRIFFIN enables a broad program of research in nuclear structure, nuclear astrophysics and fundamental symmetries with stopped radioactive beams available from ISAC and in the future ARIEL.

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