Gamma-ray spectroscopy at TRIUMF-ISAC: recent highlights and future plans

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Abstract. High-resolution gamma-ray spectroscopy is essential to fully exploit the unique scientific opportunities at the next generation radioactive beam facilities such as TRIUMF Isotope Separator and Accelerator (ISAC). At ISAC the 8π spectrometer and its associated auxiliary detectors is optimized for $\beta$-decay studies while TIGRESS, an array of segmented clover HPGe detectors has been designed for reaction studies with accelerated radioactive ion beams. This paper gives a brief overview of these facilities, recent results from the diverse program of nuclear structure and fundamental interaction studies they support and future plans.

1. Introduction

The availability of a wide variety of intense beams of exotic nuclei from the next generation of radioactive ion beam facilities such as the Isotope Separator and Accelerator (ISAC) facility at TRIUMF provides an unprecedented opportunity to address key questions of current interest in nuclear astrophysics, nuclear structure physics and fundamental symmetries. Gamma-ray spectroscopy is a powerful and versatile tool that is essential to all three areas of research at ISAC.

Short-lived isotopes are produced at ISAC by the ISOL (on-line isotope separation) method using a beam of up to 100 uA of 500 MeV protons from the TRIUMF H cyclotron to bombard thick production targets [1]. The targets can be coupled to a wide variety of ion sources including: surface, laser (TRILIS) [2] and plasma (FEBIAD) sources, to produce the world’s most intense RIB beams for certain isotopes such as $^{11}$Li. The first UC$_x$ production target was run in December 2010. This target produced high yields of short-lived neutron-rich and actinide isotopes. A license upgrade to operate UC$_x$ targets at beam currents up to 10 μA for a total of 5000 μA hr was obtained in Dec 2012.

In 2001, an RFQ and variable energy DTL provide reaccelerated radioactive beams at energies from 0.15-1.8 A MeV for nuclear reaction studies of importance in explosive nucleosynthesis environments such as Novae and X-ray bursts. Since January 2007 a Superconducting LINAC installed at ISAC-II [3] has made nuclear reaction studies possible with radioactive beams at energies up to 5 A MeV for $A < 30$. The potential for nuclear structure studies at ISAC-II was greatly enhanced in the summer of 2010 with the installation of high-beta cavities [4] which when combined with a charge state booster will provide radioactive beams up to 7A MeV for $A < 150$.

At ISAC we operate two gamma-ray spectrometers: 1) the 8π gamma ray spectrometer which has been optimized to study the $\beta$-decay of low energy ( < 60 keV ) radioactive beams and TIGRESS

1 The 8π/TIGRESS international collaboration is a consortium of researchers from 43 institutions in Canada, USA, Europe, Asia, Australia and Africa
(TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) a next generation array of segmented clover HPGe detectors that is specifically designed to meet the challenges of experiments with high-energy radioactive ion beams. An overview of these facilities, recent highlight from the research programs they support and future plans are presented.

2. Beta-decay studies with the 8π spectrometer

Over the past decade the 8π gamma-ray spectrometer has been dedicated to beta-decay studies with stopped radioactive beams at ISAC-I. The 8π is a close-packed array of 20 Compton-suppressed HPGe detectors each with a relative efficiency of ~25%, resulting in a total photopeak efficiency of 1% at 1.33 MeV. The sensitivity of the spectrometer was improved significantly by the addition of several auxiliary detectors. The β particles are detected with ~80% efficiency using SCEPTAR (Scintillating Electron Positron Tagging Array), a compact array of twenty 1.6 mm thick plastic scintillator detectors arranged in four pentagonal rings centered at approximately the same angles with respect to the beam as the four rings of HPGe detectors. This geometry provides for both high β-γ detection efficiency and bremsstrahlung background suppression, by vetoing those events where the β particle and the γ-ray are detected in the corresponding plastic and HPGe detector pairs.

The SCEPTAR array is mounted inside a spherical Delrin vacuum chamber divided into two hemispheres for easy access. An integral part of SCEPTAR is a computer controlled moving tape collector system. The low-energy (typically ~ 30 keV) beams from ISAC are focused at the centre of the SCEPTAR chamber and deposited onto a 12.7 mm wide collector tape that is fed from a large aluminum storage chamber connected to the vacuum chamber containing the downstream half of SCEPTAR. All aspects of the counting cycle can be controlled including beam on time, measurement time, tape movement and dwell time. A 5 cm thick lead shielding wall located immediately in front of the storage chamber shields the HPGe detectors from long-lived activity remaining on the tape.

The upstream half of SCEPTAR can be replaced by a pentagonal array of five SiLi detectors (PACES) for conversion electron spectroscopy measurements. In addition, a 10 element BaF2/LaBr3 array (DANTE) has been developed to provide fast timing for lifetime measurements.

The data obtained from the HPGe, SCEPTAR, PACES and DANTE arrays are collected by independent FERA data streams and software selectable triggers allow for a complete range of singles and coincidence operating modes. A more complete description of the 8π spectrometer facility can be found elsewhere [5,6]

2.1 Superallowed β-decay studies

The precision measurements of the ft values for superallowed 0+ → 0+ Fermi β-decays provide demanding tests of the Standard Model description of electroweak interactions. Such measurements have, for example, confirmed the conserved vector current (CVC) hypothesis at the level of 1.3×10^{-4}, set the most stringent limit on fundamental weak scalar interactions at (0.11 ± 0.13)% of the vector strength, and, together with the Fermi coupling constant GF from muon decay, provide the most precise determination of the Vud element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [7-9]. A significant uncertainty in these fundamental tests, however, arises from the theoretical nuclear structure corrections that are required to account for the breaking of isospin symmetry by Coulomb and charge-dependent nuclear forces [9-12]. A re-evaluation of these corrections in 2008 [12] incorporating additional physics of the core orbitals led to significant changes, which, when compared to their previously adopted values [11], lower the world-average corrected superallowed Ft value by more than 3σ and raise Vud by 1.5σ; the largest changes in these quantities in more than 20 years. These changes have led to new studies of the isospin symmetry breaking corrections in superallowed decays by a wide variety of theoretical approaches [13-17]. In order to test these models of isospin symmetry breaking, and have confidence in the CVC test and the extraction of Vud that depend on them, high-precision experimental superallowed decay data are now more important than ever.
The $8\pi$ spectrometer provides a unique tool for superallowed $\beta$-decay branching ratio measurements as the Compton-suppressed HPGe array is sensitive to $\gamma$-ray transitions originating from extremely weak $\beta$-decay branches (of order $10^{-6}$), while the high-efficiency of the SCEPTAR array provides a simultaneous measurement of the total $\beta$ activity.

In the case of the $A \geq 62$ superallowed decays, a large number of excited $1^+$ states (100 for $^{62}$Ga) are predicted to lie within the Q-value window, all of which can be fed via extremely weak beta decay branches, that could not possibly all be observed experimentally. While missing any one of these weak branches would contribute a negligible bias, the sum of all of these missed branches would represent a considerable systematic loss of total decay intensity in a process described as the “Pandemonium effect”. One can instead use the low-lying excited $2^+$ states in the daughter as collectors for the gamma-decay flux from the weak and unobserved beta-decay branches to the high-lying $1^+$ states. The power of this technique with the unique $8\pi$ experimental facility was demonstrated previously for the superallowed $\beta$-emitter $^{62}$Ga where the total superallowed branching ratio was determined to be $BR = 99.858(8)\%$. This measurement was an order of magnitude more precise than the previous adopted value and was pivotal in establishing the $^{62}$Ga $f_I$ value to the level of precision that rivals the best measured cases [18,19].

![Figure 1](image)

**Figure 1.** The $^{74}$Kr $\gamma$-ray spectra between 5000 and 6000 keV. The top panel is a singles $\gamma$-ray spectrum while the bottom two panels are bremsstrahlung suppressed $\beta$-$\gamma$ coincidence spectra.
The branching ratio for the superallowed β-emitter $^{74}$Rb was determined previous by a similar technique using two plastic scintillators to detect β-particles, two Si(Li) detectors to detect conversion electrons from the decay of the first excited 0$^+$ level in $^{74}$Rb and a single 80% HPGe detector. The value obtained was BR = 99.5(1) % [20]. A new measurement of the branching ratio for $^{74}$Rb was carried out in Nov 2010 using the 8π spectrometer. A 100 μA beam of 500MeV protons impinging on a Nb foil target was used to produce a $^{74}$Rb beam of 10000 ions/s. A total of 8 x 10$^8$ positrons were detected by SCEPTAR. A high energy (5000-6000 keV) portion of the bremsstrahlung suppressed β-$\gamma$ coincidence spectrum is shown in Figure 1. The gamma rays observed at 5684, 5228 and 5175 keV correspond to the decay of a 1$^+$ level in $^{74}$Kr at 5684 keV decaying to the ground, first excited 2$^+$ and first excited 0$^+$ levels in $^{74}$Kr with intensities of 18, 13 and 15 ppm, respectively. A total of 47 new gamma-ray transitions and 15 new levels (i.e. nine 1$^+$, five 2$^+$ and two 0$^+$) in $^{74}$Kr were observed to follow the β-decay of $^{74}$Rb which provided a measured non-analog intensity feeding the $^{74}$Rb ground state of $I_{obsgs}$ = 0.3958(70) %. When combined with a shell-model calculation to provide a theoretical estimate for the total unobserved ground state intensity this measurement should result in a factor of 3 reduction in the uncertainty of the total superallowed branching ratio for $^{74}$Rb [21]. Presently the uncertainty in the experimental $ft$ value for $^{74}$Rb is dominated by the precision of the measured $^{74}$Rb mass. This is expected to be reduced substantially once TITAN completes a high-charge state mass measurement for this nucleus [22].

The $ft$ values of the low-Z superallowed β-emitters, i.e. $^{10}$C and $^{14}$O, are of particular interest since they are ones most sensitive to a possible scalar current interaction [8]. The half-life of $^{14}$O has been determined with a precision of ± 0.02% from the weighted average of 8 measurements, two by direct β-counting and the remaining six by counting the 2.3 MeV γ ray photopeaks in the daughter nucleus $^{14}$N, that following 99.4% of the β-decays in $^{14}$O. However, a closer examination of these measurements reveals that the weighted average values of the half-life of $^{14}$O determined by the β and γ counting methods differ by 2.6 σ. A high priority program led by G.F Grinyer [23] to improve limits on weak scalar interactions through precise β and γ-ray based lifetime measurements for the superallowed emitter $^{14}$O, exploits the new technique developed for the 8π spectrometer to account for detector pulse pile-up effects in high-precision β-decay lifetime measurements via γ counting [24]. The β-counting of $^{14}$O was measured simultaneously using a zero-degree scintillator that replaced the downstream half of SCEPTAR. Representative decay curves obtained by β and γ counting in a test “proof of principle” run carried out in November 2011 are shown in Figures 2 and 3. A longer run to achieve the required statistical precision is planned for 2012.

Figure 2. Typical decay curve obtained by β-counting using the zero degree scintillator.

Figure 3. Typical decay curves obtained by all γ-ray activity and by gating on the 2.31 MeV γ-ray photopeak from the daughter nucleus $^{14}$N.
2.2 Nuclear structure studies
A diverse program of nuclear structure studies have been carried out over the past decade using the $8\pi$ spectrometer including: 1) the study of coexisting collective phases in $N = 90$ nuclei, $^{156}$Dy, $^{158}$Er, and $^{160}$Yb, populated in the $\beta$-decay of $^{156}$Ho, $^{158}$Tm and $^{160}$Lu, respectively [25], 2) a systematic study of the decay of $^{110,112}$Ag that provided a rigid test of the validity of the $\text{U}(5)$ description (modified by intruder-phonon mixing) in $^{110,112}$Cd [26] and the $\beta$-decay of the neutron-rich nuclei $^{32}$Na[27] and $^{11}$Li [28].

The production of high-intensity neutron-rich and actinide beams from UCx production targets has led recently several new initiatives. In particular, a detailed study of multiphonon excitations and mixed-symmetry states in $^{92}$Zr, was carried out via the $\beta$-decay of $^{94}$Y. In this experiment a beam of $\sim 10^8$ $^{94}$Rb ions/s ($t_{1/2} = 2.3s$) was implanted onto the tape at the center of the $8\pi$ spectrometer array for about 30 minutes to produce a $\sim 5 \times 10^7$/s source of the granddaughter nucleus $^{94}$Y ($t_{1/2} = 18.7$ min). This high-statistics $\gamma-\gamma$ coincidence data set is presently under analysis [29]. Another experiment focused on the study of neutron-rich Rb isotopes up to $^{102}$Rb, on the boundaries of the r-process path [30]. In this case the experiment was operated in a cycling mode where the beam was implanted onto the tape and allowed to decay for a short period of time before moving the tape to remove the longer-lived isobaric nuclides. This method allowed for separation of various isobars in the cocktail beam. This is illustrated in Figure 4 for an A =100 beam where the time profiles of $\gamma$-rays can be associated with transitions of a nuclide with the appropriate half-life.

![Figure 4](image.png)

**Figure 4.** Activity from an A = 100 beam from a UCx target measured as a function of the time within the cycle. Each cycle consists of 3 seconds of background, 15 seconds of beam on and 15 seconds of beam off counting. The assignment of $\gamma$-rays to the decay of specific nuclides based on their time profile is illustrated by gates on the $2^+ \rightarrow 0^+$ transitions in $^{100}$Sr and $^{100}$Zr.

3. GRIFFIN
The recent funding of GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei) will dramatically upgrade the decay spectroscopy capabilities at ISAC-I [6,31]. GRIFFIN will consist of an array of sixteen large-volume HPGe clover detectors arranged in a close-packed configuration with a total singles absolute efficiency of $\sim 17\%$ at 1.3 MeV. It has been designed to couple to all existing $8\pi$ ancillary detector systems and is also designed to work with the DESCANT neutron detector array (see section 4.1 for details) for $\beta$-delayed neutron decay studies. The new digital data acquisition system will operate at large data through-put in a semi-triggerless mode to
facilitate both high-rate nuclear structure and precision measurements to the level of better than 0.05%. GRIFFIN is scheduled for early implementation in late 2014.

4. TIGRESS
The gamma-ray spectroscopy program at ISAC-II is centered on the TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer (TIGRESS), a next generation gamma-ray spectrometer designed for use with accelerated radioactive beams at energies up to 7A MeV for A < 150. TIGRESS is comprised of up to 16 segmented clover-type HPGe detectors, each equipped with a composite BGO-CsI Compton Suppression shield. Sensitivity to the location of gamma-ray interactions within the HPGe clover is achieved through 32-fold segmentation of the outer electrical contacts, and through pulse shape analysis following 100 MHz digitization of the signal waveforms from each contact. This position sensitivity allows the detectors to be placed close to the target location without sacrificing angular resolution, leading to large gains in gamma-ray detection efficiency while retaining the high intrinsic resolution of the HPGe clover detectors. A picture of TIGRESS installed in ISAC-II is shown in Figure 5. More detailed descriptions of TIGRESS can be found elsewhere [32,33].

4.1 Coulomb excitation studies with Bambino
Light-ion Coulomb excitation studies have been carried out at TIGRESS using a charged particle detector system Bambino, designed to accommodate annular (CD) double-sided silicon detectors both upstream and downstream of the target. In these experiments the B(E2) transition matrix elements for the light-ion beams were determined relative to those for target nuclei with well-known transition strengths. The first experiment carried out during the early implementation phase of TIGRESS was a study of the mirror pair \(^{21}\text{Ne}\) and \(^{21}\text{Na}\) which resolved a previous discrepancy in \(^{21}\text{Na}\) and confirmed that the low-lying states of the mirror pair can be well described within pure \(sd\) model space by current effective interactions [34]. Other studies included the first Coulomb excitation measurements for \(^{20}\text{Na}\) [35] and \(^{29}\text{Na}\) [36].

Recently, a reorientation-effect Coulomb-excitation measurement of the sign of the spectroscopic quadrupole moment the first excited \(2^+\) state at 3.368 MeV in \(^{10}\text{Be}\) has been carried out using a beam of \(10^6\) \(^{10}\text{Be}\) ions/s at 41 MeV to bombard a \(^{194}\text{Pt}\) target. A preliminary analysis of these data gives a value of \(Q_s(2^+) = -0.06 \pm 0.07\) eb in agreement with new no-core shell model calculations with the \(CD\)-\textit{Bonn 2000}\) two-nucleon potential and large shell model spaces. The one neutron halo nucleus \(^{11}\text{Be}\) has the strongest known E1 strength between bound states and the energy weighted E1 strength up to 4 MeV exhausts nearly 70% of the cluster sum rule. A low energy Coulomb excitation measurement to
determine the E1 strength with high precision and accuracy was carried out using beams of $10^6$ $^{11}$Be ions/s at 19, 23 and 41 MeV to bombard a $^{196}$Pt target [38]. The results of this experiment will be compared with the predictions of no-core shell model plus resonating group method [38].

4.2 Transfer reactions studies with SHARC
The Silicon Highly-segmented Array for Reactions and Coulex (SHARC), a new multipurpose array for charged particle detection has been developed under the leadership of the University of York [39]. The array built for use with TIGRESS was designed to be compatible with transfer and inelastic scattering in inverse kinematics, fusion evaporation, Coulomb excitation and deep-inelastic scattering experiments. The highly segmented silicon detector array consists of two boxes of DSSSDs one on either side of 90 degrees plus upstream and downstream QQQ2 CD-detectors. The first experiment with SHARC was a measurement of the $^{25}$Na(d,p)$^{26}$Na reaction as part of a program to follow the evolution of the shell structure of neutron-rich $sd$-shell nuclei [40]. In this study a high intensity beam of $3 \times 10^7$ $^{26}$Na ions at 5A MeV was used to bombard a CD$_2$ target. The $\gamma$-rays emitted following the decay of low-lying levels in $^{26}$Na were detected with TIGRESS in coincidence with protons detected with SHARC to facilitate the measurement of angular distributions for states populated in $^{26}$Na that couldn’t be resolved with SHARC alone.

4.3 Auxiliary detector development for TIGRESS
Several new particle detection systems are under development to exploit the research opportunities with TIGRESS including a CsI(Tl) light charged-particle detector array with an integrated plunger device (TIP) for lifetime measurements to be used in fusion-evaporation studies with TIGRESS [41], SPICE (SPectrometer for Internal Conversion Electrons), a high-efficiency high-energy conversion electron spectrometer, a 70-element DEuterated SCintillator Array for Neutron Tagging (DESCANT) (see Figure 6) [42], and the ElectroMagnetic Mass Analyser (EMMA) for heavy ion recoil separation and detection [43]. All of these detector systems are scheduled for completion within the next two years.

5. Summary and outlook
During the last five years there has been a rapid development in the capabilities of ISAC to provide both low energy and reaccelerated radioactive beams for nuclear physics research. In parallel the construction of TIGRESS, a state of the art gamma-ray spectrometer, together with a suite of auxiliary detectors, and the ongoing development of GRIFFIN to replace the 8$\pi$ spectrometer, will enable the national and international ISAC user community to remain at the forefront in RIB research for the foreseeable future.

Finally, the potential for nuclear structure studies at ISAC will be greatly enhanced with construction of ARIEL, the Advanced Rare Isotope Laboratory [44]. Phase I of this project scheduled for completion in 2015 is the construction of a 25 MeV 100 kW superconducting RF electron accelerator for the production of neutron rich isotopes from the photo-fission of actinide targets. Phase two of the ARIEL project includes: increasing the e-linac energy to 50 MeV at 500 kW beam power, constructing a second 500 MeV proton beam line, and two target stations and front end mass separators; with the goal of delivering two additional RIBs simultaneously.

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