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Exotic nuclei studied with the 8pi spectrometer at TRIUMF

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Abstract. The 8pi gamma-ray spectrometer has performed decay spectroscopy experiments at TRIUMF-ISAC between 2000 and 2013. A series of ancillary detector subsystems have been developed to enable or enhance particular aspects of decay spectroscopy. This facility allows a broad range of research in the fields of nuclear structure, nuclear astrophysics and fundamental symmetries. In this contribution, an overview is given of the detector systems and the research performed with the device during its operation at ISAC.

1 Introduction

The 8pi gamma-ray spectrometer [1-4] has been operated at the TRIUMF-ISAC radioactive beam facility [5] for the past decade in decay-spectroscopy experiments. The device began operation at the Chalk River Laboratory, Canada, in 1985 with a focus on in-beam reaction experiments investigating high-spin nuclear structure. Following a brief series of experiments performed at the Lawrence-Berkeley Laboratory in California, the 8pi was moved to TRIUMF in 2000. At ISAC, it has been reconfigured for use with stopped radioactive beams and, with the addition of several ancillary detector sub-systems, has become a very sensitive and powerful instrument for radioactive decay studies. The 8pi spectrometer has enabled a diverse research program in the fields of nuclear structure, nuclear astrophysics and tests of fundamental symmetries.

2 The 8pi Spectrometer

The 8pi spectrometer consists of 20 Compton-suppressed Hyper-Pure Germanium (HPGe) detectors coupled with a series of ancillary detector subsystems to complement the capabilities of the gamma-ray spectrometer. The single-crystal co-axial HPGe detectors were constructed by Ortec and each have a relative efficiency of ~20% for 1.3 MeV photons when compared to a 3” x 3” sodium iodide (NaI) detector at a source distance of 25 cm. The typical energy resolution of the HPGe is 1.8-2.3 keV. In the configuration employed at ISAC, shown in Figure 1, the full array of twenty HPGe detectors has an absolute efficiency of around 1 % at 1.3 MeV. The front face of the detector housing has a thin beryllium window to minimize the absorption of low-energy gamma rays and maximise the low-energy efficiency of the spectrometer. These thin Be windows are complemented by the use of delrin plastic for the vacuum chambers of all ancillary detector subsystems.

Each HPGe detector is surrounded by a multi-component Bismuth Germanate (BGO) Compton-Suppression Shield consisting of a cylindrical side shield and a separate back catcher which surrounds the HPGe cold-finger cryostat immediately behind the HPGe crystal. A Hevimet collimator located at the front shields the side BGO from direct illumination from the radioactive source, as well as collimating the view of the HPGe crystal. The use of Compton suppression is a well established technique in gamma-ray spectroscopy and dramatically enhances the peak-to-background ratio of energy spectra. In decay spectroscopy this is particularly advantageous for the identification of weak transitions which would otherwise be overwhelmed by the continuum of energy events resulting from photon scattering.

The first studies with the 8pi spectrometer at TRIUMF were performed even before the low-energy beamline from the ISAC target was completed. A source of ^{176}Lu was studied to make an accurate measurement of the half-life of this isotope which is important as a geochronometer [6]. A novel technique using gamma-gamma coincidences was developed as part of the analysis to determine a half-life of 40.8 (3) x 10^9 years. In a separate study using a 15 kBq long-lived source of the $K^{\pi}=16^+$, 31-year isomeric state in ^{178}Hf^{m2}, the 8pi spectrometer was used to observe for the first time the weak direct, high-multipolarity (*M4* and *E5*) transitions which represent the direct decay from this isomer [7].

3 Ancillary Detector Subsystems

The low-energy radioactive beam from the TRIUMF Isotope Separator and ACcelerator (ISAC) facility is delivered to the central focus of the 8pi spectrometer where it is implanted into a mylar tape. Radioactive beams produced through the Isotope Separation On-Line (ISOL) method are often a cocktail of species, each with different half-lives. The decay of one or more species in the beam, or any daughter nuclei, can be a background that hinders the study of the isotopes of interest. By implanting the beam into a tape, experiments can be conducted in a cycling mode where one cycle involves a period where beam is delivered and implanted into the tape, a decay period with the beam-off, and finally the tape can be moved so the remaining radioactive sample is removed from sight of the array. In fact this section of contaminated tape is moved into the downstream tape box which is shielded from the spectrometer by a thick lead wall. When beams of a gaseous nature are studied it is advantageous to use a mylar tape with an aluminium layer. This prevents the diffusion of the radioactive

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species from the tape. The exact timings of each cycle depends on the half-lives and relative intensities of all species in the beam and their daughter nuclei. These techniques can dramatically improve the signal to background ratio of the collected data and enhance the sensitivity to low-intensity beams or weak transitions.

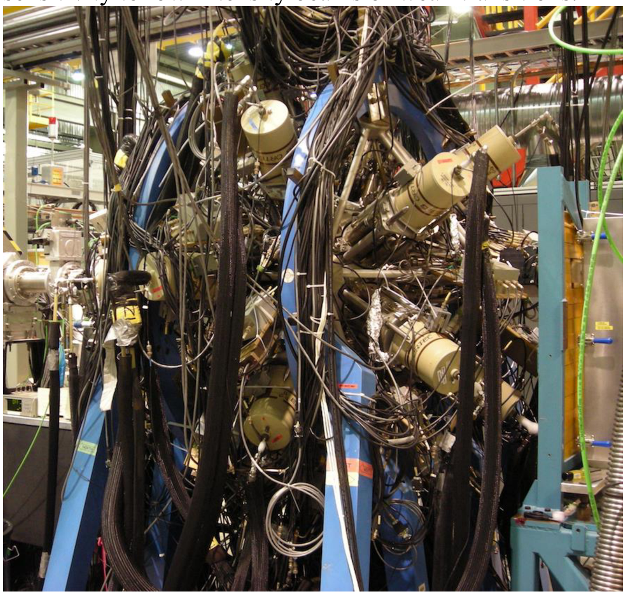

Figure 1. Photograph of the 8pi spectrometer at ISAC. The low-energy beamline can be seen on the left and the shielded tape box to the right.

In the study of beta-emitting nuclei far from the line of stability, the Q_{beta} value can become quite large, in many cases in excess of 10 MeV. Delrin plastic absorbers of ~5.5cm thickness were placed immediately in front of each HPGe front face in order to prevent the high-energy beta particles which punch through the vacuum chamber from depositing energy into the HPGe detector. The use of a low-Z material such as plastic to stop the electrons also reduces the intensity of the Bremsstrahlung radiation production which would be forward-focused into the detector. The use of these delrin absorbers will of course effect the low-energy efficiency curve of the HPGe detectors so they are not installed if an experiment seeks to detect low-energy gamma rays below ~200 keV.

An array of 20 in-vacuum 1.6 mm thick plastic scintillating paddles covering around 80 % of the full solid angle was incorporated into the vacuum chamber with light-guides coupled to out-of-vacuum photomultiplier tubes. This array shown in Figure 2 is known as SCintillating Electron-Positron Tagging ARray (SCEPTAR). It is used to detect beta particles emitted in the decay of the parent nucleus. Requiring a coincidence between a beta particle and a gamma ray within a narrow time window can reduce the contribution from room background gamma rays by around 5 orders of magnitude. This dramatically improves the signal-to-background ratio of the resultant gamma-ray spectrum and has enabled decay spectroscopy of radioactive beams delivered at a rate of just 2-3 ions/s [8,9]. The positioning of the twenty plastic scintillators in a one-to-one correspondence with the locations of the HPGe detectors allows a veto condition to be imposed between the two corresponding detectors. This allows the rejection of background in the HPGe detector associated with beta particles either stopping immediately in front, often illuminating the HPGe with Bremsstrahlung radiation, or punching-through the vacuum chamber and entering the HPGe crystal directly.

The Pentagonal Array for Conversion Electron Studies (PACES) ancillary detector can replace the upstream half of SCEPTAR with five in-vacuum semiconductor detectors for high-resolution electron spectroscopy. Each detector is a 200 cm^2 lithium-drifted silicon diode which is cooled to liquid-nitrogen temperature along with its associated Field-Effect Transistor (FET). An energy resolution of <2 keV can be achieved for discrete energy electrons in an energy range between 15 and 2000 keV. In a few cases the PACES detectors have been used to tag on alpha particles emitted in the decay of actinide beams. As alpha decay results in particle emission of discrete energy particles, their tagging is a unique selection of a particle radioactive species.

To enable the measurement of short-lifetimes of excited states in daughter nuclei, an array of 10 fast scintillators is installed in the positions between the HPGe detectors. Initially the Di-pentagonal Array for Nuclear Timing Experiments (DANTE) comprised of 10 barium fluoride (BaF_2) scintillators as described in [10,11]. Later these BaF_2 detectors were replaced with Cerium-doped lanthanum bromide ($LaBr_3(Ce)$) scintillators. A typical coincidence timing resolution below 200 ps has been achieved with this setup where the scintillating crystal size and shapes favoured higher efficiency rather than optimal timing.

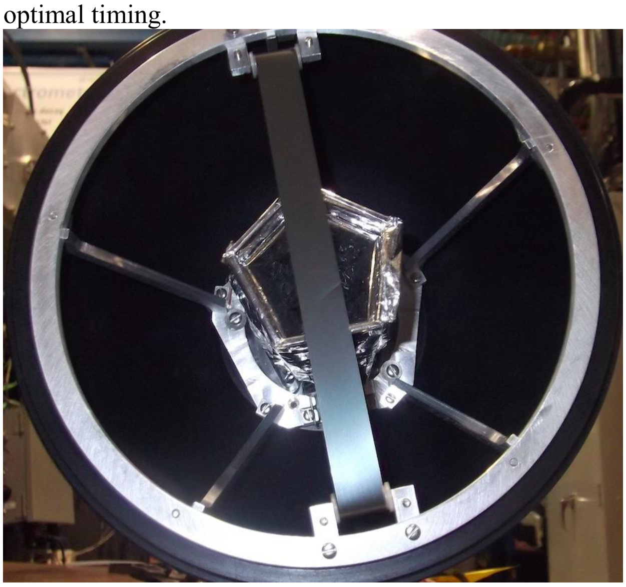

Figure 2. Photograph of the SCEPTAR plastic scintillator array surrounding the implantation location of the radioactive beam on the mylar tape.

The downstream half of SCEPTAR can be replaced by a single circular BC422Q scintillator detector mounted at zero-degrees to the beam axis. This scintillator, coupled to an in-vacuum photomultiplier has an excellent timing response to beta radiation. The small distance from the implantation point of the beam on the tape leads to a large solid angle of approximately 25% for good beta efficiency. The fast signal from this scintillator can be used as a stop signal for the DANTE Time-to-Analogue Converter (TAC) modules in order to allow beta-gamma coincidence fast-timing measurements. This can provide higher statistics than the gamma-gamma measurement and access to excited states which are fed directly in beta decay but decay directly to the ground state.

4 Data Acquisition System

The data acquisition system of the 8pi spectrometer is designed to allow for high-data-through-put while providing an easy way to quickly implement complex triggering logic between detector types. Often the different detector types are counting at very different rates. To achieve this the data acquisition system is divided into four data streams representing the four main detector sub-systems; the Compton-suppressed HPGe, SCEPTAR, DANTE and PACES. These four streams separately use analogue NIM electronics to process energy and timing signals, and to provide a pre-trigger for that stream to the Master triggering logic.

The pre-triggers from the four streams are fed into a single CAMAC logic unit where master-triggering decisions are processed based on the multiplicity and temporal overlap of pre-triggers from each of the data streams. Master triggers are then issued separately to each data stream in order to initiate data readout from that stream. In this setup, one can easily allow the acceptance of singles from one data stream while simultaneously requiring a coincidence between any two data streams, as well as much more complex conditions.

Energy and timing signals are digitized in FERA ADC or TDC modules where readout is initiated upon the issuing of a Master trigger to each individual stream. The data is then passed to VME-FIFO units for ultimate writing to data disk. Other signals that allow precision measurements to be achieved are also recorded such as pile-up flags and multiplicity levels. Each stream has a timestamp associated with every event through use of a centralized 10 MHz ovenized oscillator and a FERA Universal Logic Module (ULM) in each FERA chain. The maximum data rate of each stream is separately limited by the FERA bus transfer speed and therefore the total system data rate can surpass this. A sustained data-rate of 12 MB/s is often achieved during measurements with intense radioactive beams.

5 Research Program

The 8pi spectrometer has been used for a wide range of research in nuclear structure [12-21], nuclear astrophysics and fundamental symmetries [21-33] using stopped radioactive ion beams provided by the ISAC facility. Figure 3 gives an overview of the regions studied and as can be seen this spans almost the entire nuclear chart.

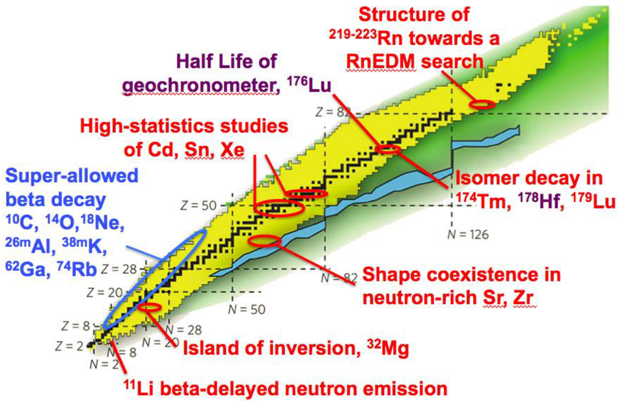

Figure 3. Studies performed using the 8π spectrometer at ISAC.

The fundamental symmetries program with the 8pi spectrometer [21-33] has focused on making precision measurements of super-allowed beta decay in order to provide fundamental tests of the description of electroweak interactions in the Standard Model [34]. In these tests it is the Q_{beta}, branching ratio and half life of the super-allowed emitter which must be determined with a fraction of a percent precision. The 8pi spectrometer at ISAC has determined half-lives through the detection of gamma rays and from the detection of beta particles using the zero-degree scintillator [23] as well as branching ratio measurements involving betas and gamma rays. The 8pi spectrometer has made thirteen precision measurements for seven of the super-allowed emitters ranging from ^{10}C to ^{74}Rb [21-33].

The heaviest of these, ^{74}Rb, now has the value for the ground state branching ratio known to 600 (300) parts per million [21], 99.545 ± 0.031 %. This is a very challenging measurement due to the so-called Pandemonium effect [35]. The decay from the parent state that does not proceed directly to the ground state is fragmented across hundreds of very weak transitions where it is therefore practically impossible to observe them all. Such precision can be achieved by inferring this intensity from the feeding of 2^+ levels close to the ground state. These 2^+ levels are not fed directly in the beta decay but rather act as collector states for the weak feeding to the many 1^+ states.

The V_{ud} element of the CKM quark-mixing matrix is now by far the most precisely determined with a value of $|V_{ud}|$ = 0.97425 ± 0.00022 [34], and together with the other elements in the top row makes the most demanding experimental test of the unitarity of the CKM matrix which presently has a value of 1.00008 ± 0.00056 [34].

The 8pi spectrometer has made many studies looking at various aspects of nuclear structure. One example is the first observation of a $K^{\pi}=0^+$ isomeric state in ^{174}Tm [18,19] which has a half life of 2.29 (1) secs. In this case the combination of gamma-ray and internal conversion electron spectroscopy was used to determine the decay transitions and their multipolarities. The interpretation of the de-excitations from this isomeric state suggests that it is primarily proton excitations involved and that this is a good example of a *K* isomer.

High-statistics beta-decay studies of nuclei close to stability have provided new insights into nuclear structure through the identification of very low-intensity decay branches. Examples of this type of investigation include the stable Cd [13-16] and Sn [36] isotopes. In the cadmium nuclei a series of detailed spectroscopic studies involving not just decay spectroscopy but also transfer reactions and inelastic excitation have shown that the states originally labelled as the second, or even third, phonon vibrational excitations do not demonstrate the transitional strength to support that interpretation and point towards a more gamma-soft ground-state configuration together with intruder states [13].

In some cases these very weak decay branches can carry a significant amount of the transition strength. This is the case in ^{94}Zr [12] were the observation of a weak 371 keV transition completely changes the interpretation of this nucleus. This 371 keV transition represents the 2^+ to 0^+ transition of a quite well-deformed configuration which is co-existing at low energy with the near-spherical ground state configuration. This in fact represents the first observation of shape co-existence in the form of a particle-hole excitation across a sub-shell closure, rather than across a major shell gap.

Numerous other beta-decay studies have been carried out across the chart of nuclides including extending the level scheme of ^{32}Mg [8,9] at the centre of the island of inversion, and halo properties involved in the decay of ^{11}Li [17]. Recently, with the development of actinide targets at ISAC, several experiments have been performed with neutron-rich beams to study shape coexistence around N=60, isotopes which lie at the boundary of the island of inversion [37], and the properties of nuclei in the proximity of the astrophysical rapid neutron-capture process (*r*-process) [38].

6 Summary and Outlook

The 8pi spectrometer has now been relocated to Simon Fraser University in Burnaby, British Columbia. The device will be reconfigured, including use of the original 4pi inner BGO ball, to study the properties of isotopes produced in spontaneous and induced fission.
At ISAC, the Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) facility [39] has now been commissioned to replace the 8pi spectrometer for decay spectroscopy studies of stopped radioactive beams. The GRIFFIN array of 16 HPGe clover detectors used in conjunction with all the ancillary detector subsystems developed for the 8pi spectrometer represents a factor of nearly 300 enhancement in gamma-gamma coincidence efficiency at 1.3 MeV. The detectors will be coupled to a custom-designed and built digital data acquisition system which will enable decay spectroscopy experiments of unparalleled sensitivity for studying low-intensity beams or decay transitions with very small branching ratios.

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