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The TRIUMF-ISAC gamma-ray escape suppressed specrometer, TIGRESS

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Abstract The TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer is a high energy-resolution, high efficiency γ-ray detector array for radioactive beam experiments. It consists of high-purity germanium detectors with scintillator suppressors and waveform digitization. TIGRESS can operate in modes optimized for either maximum efficiency or for high peak-to-total, and can switch between these modes within a day. The digitized waveforms provide 6 mm FWHM position resolution for incident ^{137}Cs γ rays. The array hosts a suite of auxilliary detectors for charged particles and neutrons.

Keywords In-beam γ-ray spectroscopy · Accelerated radioactive beams

1 Background: scientific motivation and design goals

Some of the most exciting recent results in nuclear structure are associated with the evolution of novel nuclear behavior at the extremes of nuclear existence [1, 2], including (but not limited to) halo nuclei [3, 4], dissolution of the near-stability shell gaps [5, 6] and emergence of new magic numbers with special stability [7], and proton-neutron pairing [8]. These behaviors can be explored through the measurement of the excitation properties of exotic nuclei, for example through in-beam γ-ray spectroscopy with accelerated exotic radioactive ion beams (RIBS).

ISAC and ARIEL: The TRIUMF Radioactive Beam Facilities and the Scientific Program.

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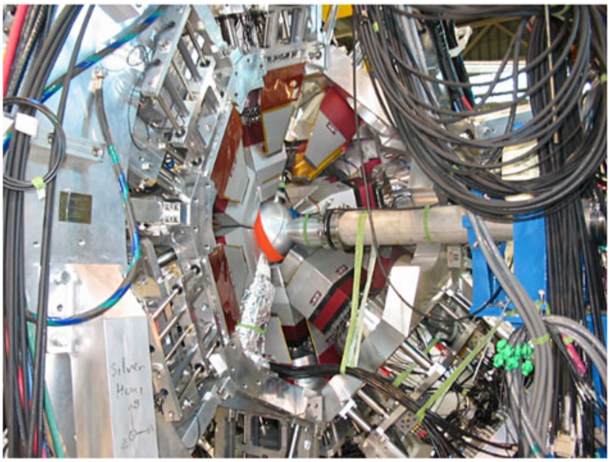
Fig. 1 TIGRESS, with 12 detectors in the close-packed configuration



Heavy-ion collisions at or above the Coulomb barrier with RIBs directed upon stationary targets can lead to a wide range of reaction channels and excitation modes. Nuclei excited in the collision process will then emit one to ~40 γ rays, with typical energies from ~50 keV to ~8 MeV. These emitting nuclei will be fast-moving sources ($v/c \simeq 0.03$ to 0.10) so the detected photons will be Doppler shifted in the laboratory frame. These features generally point towards high purity germanium (HPGe) detectors with anti-Compton shields and with high accuracy in γ-ray vector determination. In RIB experiments, beams intensity is limited by RIB production technology and cannot be easily increased, which implies that high total γ-ray detection efficiency cannot be sacrificed. Also, the most sensitive experiments require the use of additional sophisticated radiation detectors, such as heavy-ion recoil spectrometers, light-ion counter arrays, neutron detectors, and conversion electron spectrometers, which requires due care in the mechanical layout of the γ-ray detectors to accomodate these. Finally, to maximize the physics output of a RIB facility, the experimental end-stations must allow for rapid reconfiguration; campaigns on a given production target will drive the beam scheduling moreso than experimental setups [9].

The TRIUMF-ISAC Gamma Ray Escape Suppressed Spectrometer, TIGRESS, is used at the ISAC-II facility [10] primarily for RIB experiments. It consists of up to 16 units of so-called clover HPGe multi-crystal detectors. Each clover is outfitted with a set of scintillator suppressor shields. The scinitllators and clovers are designed so that the HPGe may be inserted to a high-ϵ mode with maximum photopeak efficiency, or inter-clover suppressors may be inserted for a high-PT with maximum escape suppression and hence peak-to-total (or peak-to-background) ratios. The design was specified such that the array can be completely reconfigured from high-ϵ to high-PT and back in under a day. Waveforms from the detectors are sampled by 100 MHz 14-bit flash ADCs, with energy, timing, and pretrigger information derived by digital signal processing on high-density FPGAs. Trigger, clock, and data are transferred from multi-channel ADC/FPGA units to multi-level trigger and data collector cards. At the top level the trigger is validated and read requests are broadcast to the ADCs. TIGRESS has operated with arrays of highly

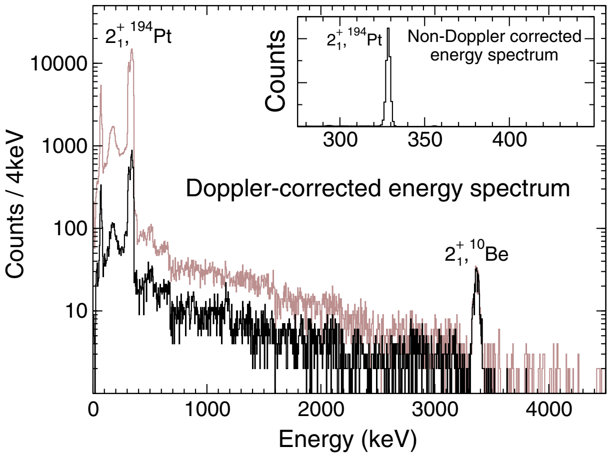


Fig. 2 Gamma-ray energy spectrum from inelastic scattering of ^{10}Be [11]. The *grey* spectrum shows the full γ-ray spectrum in coincidence with a heavy ion, while the *black* spectrum was gated on heavy-ion energies in a range expected for 3.386 MeV projectile excitation

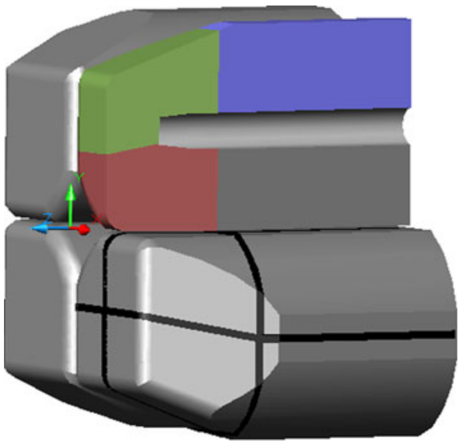


Fig. 3 Schematic showing HPGe outer contact segmentation and cutaway view indicating volume spanned by outer contacts

segmented silicon detectors for charged-particle detection, and will also be used with plunger, CsI(Tl) detector, neutron detector, and recoil separator auxilliary devices. Figures 1 and 2 show the array in its configuration for experiments in 2011 and a representative spectrum from a RIB experiment respectively.

2 Segmented HPGe clover detectors

The high energy-resolution γ ray spectrometers in TIGRESS consist of four HPGe n-type bulleted-coaxial detectors in a single cryostat [12]. The crystals are nominally 60 mm in diameter and 90 mm long before they are machined and tapered (Fig. 3). Each crystal has a photopeak efficiency of $\geq$38 % relative to the ^{60}Co NaI(Tl) standard [13]. The cryostat, whose shape is identical to the EXOGAM [14] clover detectors, is also tapered. This allows for close-packing of the detctors in a rhombicuboctahedron (truncated cube) geometry. The inner-core coaxial contact

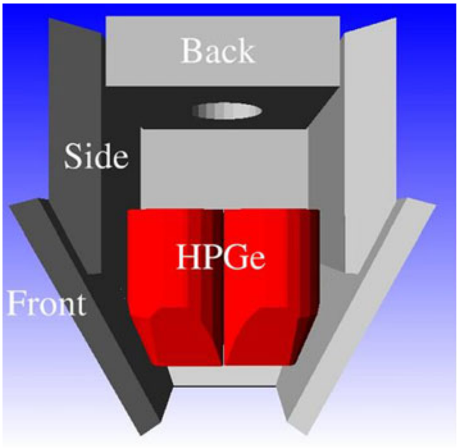


Fig. 4 Suppressor layout in the high-peak-to-total configuration

holds positive bias and collects charge from the full volume of the crystal. The outer surface of the detector has eight electrically isolated contacts, with four quadrants around the axis of the core contact and a lateral segmentation 30 mm from the front of the crystal. The center contact is instrumented with a cold FET and feedback front-end network within the cyrostat volume, while for the outer contacts the network is at room temperature. All contacts are instrumented with charge-sensitive preamplifiers.

In multi-crystal detectors such as the TIGRESS detectors, γ rays that enter one crystal and escape have a high probability of striking another crystal. The incident photon energy, then, can be measured by adding the energy deposition in two (or more) neighboring crystals. This add-back results in a relative efficiency for a full TIGRESS clover detector of between 215 and 220 %, depending on the efficiency of the individual crystals in the cryostat.

3 Escape suppression shields

Each clover is also outfitted with a set of scintillators [15] to detect escaping photon energy as shown in Fig. 4. Four CsI(Tl) crystals in two enclosures, and an eight-crystal BGO side-catcher in a single, hollow square, are bolted to the clover cryostat. These are backplug and sidecatcher suppressors, respectively, and detect small-angle scattering out the back and flat (orthogonal) side of the cryostat. An additional set of eight BGO scintillators arranged in pairs into trapezoidal enclosures fit around the front, tapered part of the clover cryostat for large-angle Compton scattering, especially from the front of the HPGe volume. Light from each scintillator is detected in a pair of phototubes and read with a single charge-sensitive preamplifier [16]. The segmentation of the suppressors allows for application of a wide variety of suppression strategies, depending on the expected energy and multiplicity of γ rays in the specific experiment; this has been investigated in detail [17].

The clover detectors with their fixed suppressors are mounted on a carriage that allows the unit to be inserted and withdrawn through the sixteen square faces of a truncated cube, with the ion beam entering and exiting through the other two square faces. The front suppressors enter the array through the edges of the truncated cube squares. This allows the clovers to be pushed forward so the fronts of the cryostats circumscribe an 11.0 cm radius sphere. This is the high-ϵ configuration. As an alternative, the clovers, together with their fixed suppressors, may be withdrawn to a radius of 14.5 cm, and the front suppressors inserted between them. In this configuration, the front tips of the suppressor collimators are also inscribed by an 11.0 cm radius sphere. In this configuration the front scintillator plates afford the maximum coverage for large-angle Compton scattering, and as such is the high-P/T mode. The original design specified that it should be possible to reconfigure between the high-P/T and high-ϵ modes in under a day.

The mechanical support structure holds eight clover and suppressor units on a central corona perpendicular to the beam axis, and four more at each of 45° and 135° to the beam axis. These parts of the frame supporting the off-perpendicular positions are referred to as front and back lampshades respectively. The lampshades and their clovers may be removed to accomodate large downstream detector or optics devices. This was anticipated primarily for large-acceptance downstream recoil spectrometers but can also be used to accomodate heavy-ion gas counters or counters for (forward-focused) neutrons following heavy-ion reactions.

During the 2010 experimental campaign, TIGRESS was outfitted with ten clover units (including suppressors) on the central corona and backward lampshades, to accomdate the SHARC silicon detector array described below. The campaign began with the array in high-P/T mode. This partial TIGRESS array was measured to have an absolute photopeak efficiency of 4.7 %, including addback. During a break between experiments, the array was reconfigured in one hour to the high-ϵ mode. In this configuration and with SHARC still in place, the absolute photopeak effiency was 7.4 %. This included addback within a clover unit but not between neighbouring cryostats.

4 Data acquisition system

The data acquisition system [18] uses a hierarchal, scalable multi-level triggering system and digital waveform sampling. Signals from the HPGe and suppressor charge-sensitive preamplifiers are digitized by TIG-10 modules. Each of these VXI-C modules consists of ten channels of 100 MHz 14-bit flash ADCs. The waveforms are continuously sampled. Contemporaneously, a large FPGA on each channel evaluates features of the waveform in real time. A clip-delay and leading-edge discriminator are evaluated for two pretriggers; the first validates the signal as a possible valid radiation event (a hit), while the latter is used in the triggering system (a Level 0 trigger). A hit triggers the evaluation of the amplitude of the signal by a moving-window pole-zero-corrected algorithm and a digital implementation of a rise-time-compensated constant fraction discriminator (CFD).

The Level 0 per-channel pretriggers are evaluated on the TIG-10 to generate four possible Level 1 triggers. These are transmitted by time-division multiplexing over an LVDS serial link to the next trigger level in TIG-C collector cards. These VME cards have thirteen ports, twelve of which communicate with lower-level cards such as TIG-10 digitizers. Up to four Level 2 triggers are evaluated based on the Level 1 trigger inputs. These are transmitted by the remaining port up to a

TIG-M Master card, which is physically identical to a TIG-C card but with special master firmware installed. Once a master trigger is evaluated it is sent back down to the lower levels through the TIG-Cs ultimately to the TIG-10 digitizers. At this point the digitized signal trace and evaluated features (energy and time) are validated and queued for transmission. The serial link is also used to transmit the TIG-10 data to the TIG-Cs, where they are stored in a FIFO for readout over the VME backplane into an frontend computer. Parameters for clipping, hit and trigger threshold, energy evaluation, CFD delay and threshold are transmitted through from the VME computers through the TIG-Cs, then to the TIG-10s via the LVDS interface as well. Run control and data storage are managed by MIDAS [19].

5 Position sensitivity

As has been noted previously, TIGRESS is intended for in-beam γ-ray spectroscopy of accelerated RIBs, and as such the emitted γ rays are Doppler shifted. The laboratory-frame γ-ray energy must be transformed into the rest frame of the emitting nucleus of interest. This requires knowing the direction of the γ ray and also the velocity and direction of the emitting ion when the emission occurs. High granularity charged-particle detectors are common and straightforward to use. While the slowing down of a beam in target prior to or after the nuclear reaction prior to γ emission results in an uncertainty in the velocity, this is often small. The largest contribution often comes from γ-ray detection. With an unsegmented detector, the uncertainty in the γ-ray direction is the opening angle of the detector. In the case of TIGRESS detctors in the close-packed configuration, this is approximately 20° and, although it depends in detail on the γ-ray energies and source velocities, the resulting uncertainty in Doppler correction will result in a peak with an order-of-magnitude poorer energy resolution than the intrinsic resolution of HPGe. The eight-fold electrical segmentation of TIGRESS can provide an effective granularity of $\sim$10°. To approach Doppler broadening of the same magnitude as the intrinsic resolution of HPGe over a wide range of experimental conditions, it is necessary to measure the incident γ-ray direction to $\sim$3° or better. This corrsponds to an effective pixel size of $\sim$8 mm in position, in a plane perpendicular to the direction of γ-ray emission. It also requires reconstruction of the γ-ray multiple scattering within the detector, at least to the extent of identifying the most-probable first interaction corresponding to the incident photon vector. This puts a more challenging constraint of measuirng individual interactions with an uncertainty of better than $\sim$5 mm position reconstruction in three dimensions, which is why the TIGRESS outer contacts are segmented longitudinally. Early investigations with a TIGRESS prototype showed that the TIGRESS detector geometry exhibited a sensitivity of 0.44 mm [20] as defined in [21].

The horizontal position resolution of TIGRESS clovers is demonstrated with a collimated ^{137}Cs source using a technique similar to those applied in the large tracking arrays [22]. Electric fields and weighting fields for the TIGRESS geometry are calculated with FEMLAB [23]. Electron and hole trajectories are calculated for various initial positions in the crystal, using the mobilities of [24]. From these, the time- and interaction-position-dependent charge collection waveforms are calculated and then convolved with the PSPICE calculated response of the TIGRESS pream-

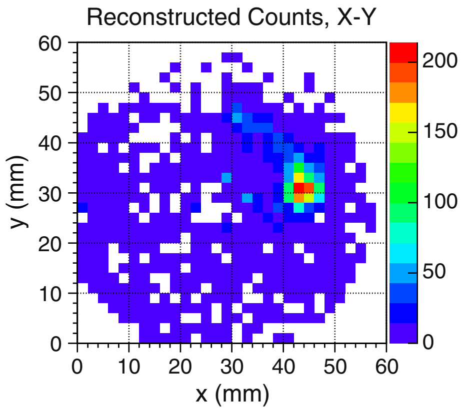


Fig. 5 Reconstructed first-interaction location for a collimated 662 keV γ ray

plifiers. Also, a representative set of single-interaction measurements, employing the concidence measurement technique described in [21], are collected using a small TIG-10-based data acquisition system. Like other highly segmented detectors [25], the TIGRESS detectors exhibit linear and differential crosstalk with a magnitude comparable to the expected induced signals. The differential crosstalk is simulated by an RC-CR transfer function, and both the amplitude of crosstalks (linear and differential) and the time constants of the transfer function are fit to the subset of coincidence measurements. The cross-talk is then included in the signal calculations to generate a set of basis waveforms on a uniform lattice of (1 mm)^3 voxels. The TIGRESS clover was illuminated with the collimated source and waveforms were collected with no coincidence condition. The basis waveforms were searched by minimizing a figure of merit similar to a χ^2 but with a power of 0.7 rather than 2. The minimization assumes one interaction first, but if the figure of merit is poor, a second search is undertaken with two interactions, either two in one segment or one in each of two segments. The search starts by comparing against a coarse, regular subset of the calculated basis waveforms in 8 mm steps over the entire detector volume, then narrowing the search volume and increasing the granularity of the comparison by factors of 2. The highest-energy interaction is taken to represent the most probable position of the incident γ ray. Figure 5 shows the reconstructed position of 662 keV γ rays based on measured waveforms for a collimated source incident at a given position. The full-width at half maximum of this position peak above background is 6 mm, which includes both the uncertainty in reconstruction and the divergence from the 1.5 mm diameter, 7 cm long collimator for the ^{137}Cs source.

6 Auxilliary detectors

Every experiment with TIGRESS to date has used a silicon charged particle detector. The BAMBINO facility, shown in Fig. 6, was used in the first TIGRESS experiments. BAMBINO consists of up to two S2 or S3 CD-style [29] segmented annular detectors and feedthroughs. The two CDs may be arranged as a dE-E telescope or may be placed on either side (upstream and downstream) of the target ladder, which hold

Fig. 6 BAMBINO facility installed at TIGRESS, with the side access panel of the scattering chamber removed, showing one S3 detector mounted downstream of the target location with a blank collimator plate in place of an upstream detector

up to five targets or apertures and which can be biased to suppress delta electrons. The nominal position places an S3 detector 30 mm either upstream or downstream of the target ladder. At those position, two S3 detectors will span laboratory-frame polar scattering angles from 20° to 49.4° at forward angles or 131.6° to 160° at backwards angles, for a total angular coverage of 3.63 srad, or 28.9 % of a full sphere. The innermost rings subtend 1.66° while the outer rings subted 0.82°. Azimuthal angular resolution is 11.25°, given by the 32 sectors of the S3 detector. The target chamber vacuum vessel is made of aluminum and has an outer radius of 102 mm (diameter 8″) and thickness of 1.5 mm (0.06″). The S3 holder is designed so that with appropriate standoffs it may be placed anywhere from 3 mm to 70 mm from the target. The Si signals are processed through charge-sensing amplifiers [16] with nominal sensitivities of 10 or 100 mV per MeV, respectively. The Si signals have <100 ns rise times and a decay constant fall time of ~80 μs , very similar to the signals from the HPGe detectors. This makes it very straightforward to integrate them into the triggering, waveform processing, and data acquisition system; they are read out by TIG-10 modules. Further descriptions of the BAMBINO facility and experements may be found in [4, 6, 26–28].

More recently, TIGRESS has been used with the Silicon High Angular-resolution detector for Reactions and Coulex, SHARC [30]. This is a barrel of up to eight double-sided strip Si arranged in boxes of four detectors each fore and aft of the target location detector, and up to eight quadrants of annular-sector detectors closing the ends of the barrel (see Figs. 7 and 8). The rectangular box detectors have 48 and 24 segments respectively. This provides an angular resolution on average of approximately 1°, depending on the angle. The total geometric coverage of a fully populated SHARC array is 90 %, although contact wires, inter-strip dead layers and such reduce the total effective angular coverage to 2π sr. In the first campaign only one-half of the Si detectors and eight clover detectors were used, so all detectors were read with TIG-10 modules. In a subsequent campaign, the Si were read out with higher-density TIG-64 cards, which include 64 14-bit 50 MHz flash ADCs in a VME package. Like the TIG-10 cards, the TIG-64s generate level-1 triggers and

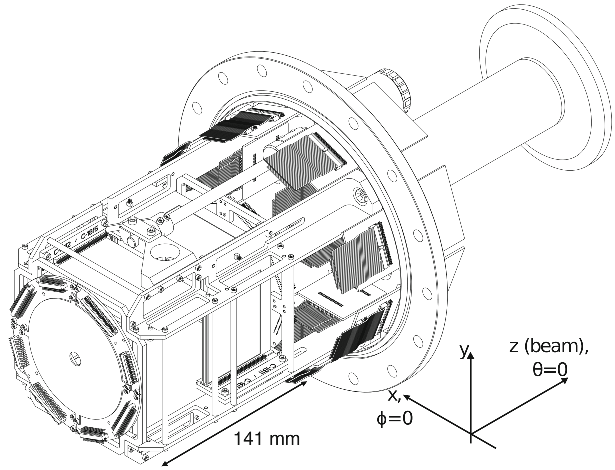


Fig. 7 Line drawing of SHARC, adapted from [30]

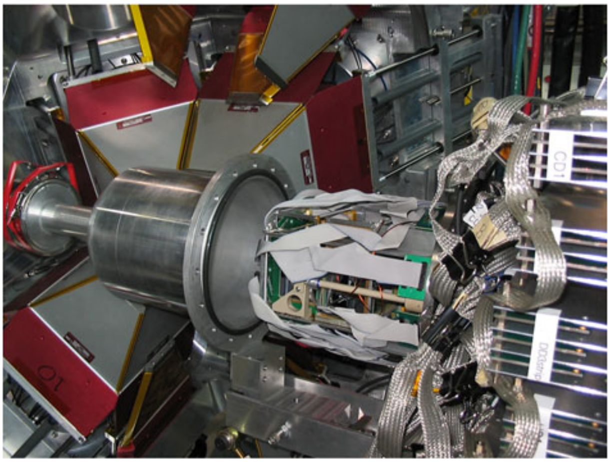


Fig. 8 Photograph of SHARC about to be inserted into its scattering chamber at TIGRESS

transfer trigger, global accept, and evaluated energy, time and waveform information to TIG-C cards by the same LVDS protocol.

7 Future prospects

In addition to silicon detectors, other auxilliary detectors are in development and expected to become available over the next few years. The TIGRESS Integrated Plunger [31] will combine radiation-hard scintillators and a plunger apparatus for lifetime measurements in exotic nuclei produced by weak fusion-evaporation channels. Tests of small commercially available PIN diodes and of CsI(Tl) detectors have been undertaken towards this goal. Also, a deuterated liquid scintillator array can replace the downstream lampshades for neutron detection, DESCANT [32]. SPICE, an in-beam electron spectrometer with permanent magnet electron transport and silicon detectors, is under development [33]. TIGRESS will also be compatible with the ElectroMagnetic Mass Analyzer, EMMA, a high-resolution, high-acceptance recoil separator that will be available for experiments in the coming few years [34].

The data acquisition system is continuously being refined and upgraded for new experimental opportunities. A new class of 1 GHz digitizers compatible with the rest of the TIGRESS readout are being developed, to allow for neutron-γ discrimination based on DESCANT pulse shapes. Currently the data bottleneck is that the collector cards are read out over the VME backplane by a single VME processor. The collector card firmware is being upgraded to allow parallel, simultaneous readout of the data by multiple VME processors. The energy and time evaluation algorithms have also been rigorously investigated and optimized to maintain excellent energy resolution and timing at count rates in excess of 10 kHz. These data acquisition upgrades have been in regular operation since 2012.

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